The Metamorphic and Structural History of Glenelg, NW Scotland

Christopher James Salt

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Now our partnership is dissolved, I feel so peculiar,
As if I had been on a drunk since I was born
And suddenly now, and for the first time, am cold sober,
With all my unanswered wishes and unwashed days
Stacked up all around my life; as if through the ages I had dreamed
About some tremendous journey I was taking,
Sketching imaginary landscapes, chasms and cities,
Cold walls, hot spaces, wild mouths, defeated backs,
Jotting down fictional notes on secrets overheard
In theatres and privies, banks and mountain inns,
And now, in my old age, I wake, and this journey really exists,
And I have to take it, inch by inch,
Alone and on foot, without a cent in my pocket,
Through a universe where time is not foreshortened,
No animals talk, and there is neither floating nor flying.

W. H. Auden
From "The Sea and the Mirror"

ABSTRACT

The Glenelg peninsular in NW Scotland contains Lewisian type rocks occurring east of the Moine thrust that have been metamorphosed and deformed along with the Moine rocks. These Lewisian rocks can be split into two facies, the Eastern Lewisian and the Western Lewisian, always separated by a thin strip of highly deformed Moine rocks.

The Eastern Lewisian contains a wide variety of metamorphosed igneous and sedimentary rocks including eclogites and websterites, marbles, eulysites and kyanite - bearing pelites. The eclogites are the best exposed of these rocks. They were metamorphosed at 730°C,>15 Kb, which produced a coarse grained garnet - clinopyroxene - bearing rock. The rocks were later intruded by granitic melt that tended to fill cracks within the rock to produce quartz - feldspar - kyanite streaks, particularly within the eclogite. In some eclogites there was limited partial hydration to produce phases such as biotite and hornblende co - existing with the eclogite minerals, in others recrystallisation to produce quartz rich eclogites. The rocks were then locally deformed and recrystallised at about 780°C,>17 Kb. They were then partly retrogressed during uplift, with the breakdown of Na - clinopyroxene to form symplectites of diopside and plagioclase in particular, prior to the deposition of Moine sediments. The Moine and Lewisian rocks then together underwent at least three periods of deformation. The first period of deformation was the most intense, producing a strong foliation in amphibolites derived from the eclogite. The second and third periods of deformation were less intense, generally folding this earlier fabric, although distinct slides occurred within both the Moine and the Lewisian. The peak of metamorphism, at ≈ 600 - 700°C and > 8 Kb occurred after the second deformation with the growth of randomly oriented amphibole and mica in many of the rocks. During these deformation events some eclogite was preserved as pods within otherwise deformed and retrogressed equivalents which were periodically cracked during the ductile deformation of the surrounding rocks, with the cracks filled by a variety of different minerals at different times, whose growth corresponded to that of similar minerals in the surrounding rocks. Other rocks in the Eastern Lewisian are poorly exposed and mostly only show deformed amphibolite facies rocks similar in texture to the deformed eclogites, but in places patches of coarser grained rock, often with intrusions of quartz - feldspar - kyanite, are preserved suggesting that the metasediments had a similar history to the eclogites. Within the marbles there are occasional nodules of meta - igneous rock, often either eclogite or pyroxenite, that have equilibrated with the marble to produce Ca - rich equivalents of the eclogites but that

nevertheless show similar textures to the eclogites and often have quartz - feldspar - kyanite veins.

The Western Lewisian contains no recognisable meta - sediments, only a variety of meta - igneous rocks. Eclogite is rare, only occurring at one locality as pods within otherwise deformed amphibolite facies rocks. These eclogites exhibit broadly similar textures to the Eastern Lewisian eclogites, but have a slightly different chemistry, being more Si rich and Ca poor. They were formed under similar conditions of about 760°C,>15 Kb, but only one metamorphic event has been distinguished. Many of the amphibolites of the Western Lewisian have similar textures and chemistry as partly retrogressed Western Lewisian eclogite. These rocks were deformed to produce a weak fabric prior to the intrusion of further basic material that is texturally and chemically different to the eclogites. All of these rocks were then deformed and metamorphosed by the syn - Moine deformation as outlined above for the Eastern Lewisian.

It is suggested that the Eastern and Western Lewisian rocks share a common history of initial high - pressure metamorphism, then the intrusion of granitic melt prior to further high pressure metamorphism. This was followed by deformation and partial retrogression before the intrusion of basic and ultrabasic dykes. The Lewisian rocks were then exhumed and the Moine rocks deposited onto them prior to further deformation and metamorphism. Radiometric dating suggests that the high pressure metamorphism occurred at approximately 1050 Ma (Grenville), but field and petrographic evidence suggests that the Lewisian rocks have undergone a similar history to the Scourian rocks of the main Lewisian outcrop and that Grenville ages for the rocks date initial syn - Moine metamorphism.

Acknowledgements

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List of abbreviations used

Mineral abbreviations are after Kretz (1983).

Fe''	: Fe^{2+}
Fe'''	: Fe^{3+}
GR	: grid references of localities, national grid square NG, O.S. 1:50,000 sheet 33
Kb	: kilobars (0.1 GPa)
K_D	: distribution coefficient
Mg no.	: Mg/(Mg+Fe). For garnet and pyroxene, Fe = Fe'', for all else Fe = Fe(tot)
marble	: refers to all carbonate rocks regardless of MgO and SiO_2 content
pyroxene	: refers to clinopyroxene
SN.	: sample number (listed in appendix I)
wt %	: weight percent of oxide

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PART ONE
Introduction

Chapter One

Introduction

CHAPTER 1

Introduction

The Glenelg inlier is the largest of a number of Lewisian inliers within the Moine. It stretches for thirty km from Attadale on Loch Carron to Arnisdale on Loch Hourn. Lewisian rocks found east of the Moine thrust on the Sleat peninsular of Skye are probably part of the same inlier. The inlier is of particular interest because it contains a wide variety of metamorphosed igneous and metamorphic rocks, and because some metabasic rocks preserve eclogite facies relicts within otherwise amphibolite facies schists. The main aim of the thesis is to describe and interpret the geological history of the inlier, in which supposedly Lewisian rocks metamorphosed at high pressure and temperature have later been deformed and retrogressed along with younger Moine rocks.

The structure of the area has been described by many authors, principally Ramsay (1958, 1960, 1963), and was updated by May *et al.* (1993), although they dealt principally with rocks immediately to north of Loch Duich. Three major deformation events were identified, along with a minor fourth event. The first of these events (D_1) resulted in the formation of strongly deformed rocks that were either sheared or isoclinally folded. The second event (D_2) produced at least two large scale folds south of Loch Duich, an antiform and a synform, in which the younger Moine rocks form the lowest structural unit. Minor folds occur throughout the area. A weak crenulation cleavage has formed in many rocks due to the alignment of micas and amphibole. May *et al.* (1993) suggest that sliding occurred both within the Moine and Lewisian and also along some of the boundaries between them, principally forming the central Moine strip. The third event (D_3) possibly occurred in a different deformation cycle, resulting in further folding, including one large fold and many associated minor folds. The intensity of deformation increased to the east. Most of the Lewisian of the Glenelg peninsular lies on the western limb of this fold. The last (D_4) event produced cracks and local brittle folds, associated with movements along the Moine thrust.

The early metamorphism has been principally described by Alderman (1935) and Sanders (1972, 1978, 1988, 1989), amongst others. Alderman described the occurrence and retrogression of the eclogites. Sanders described the high pressure metamorphism of the rocks in more detail and began to relate such metamorphism in the metabasic eclogites to the sediments. He showed that all the Eastern Lewisian rocks had been metamorphosed at about 16.5 Kb, 750°C. Sanders *et al.* (1984) dated the eclogites as being ≈ 1050 Ma old.

The original aims of the thesis were to produce a detailed structural interpretation of the area, with a history interpreted from a rigorous re - interpretation of the structure. Lack of exposure caused the project to be altered to a hybrid investigation of the petrology and chemistry of the rocks based upon limited field work, and large scale re - interpretation of the structure of the area has not been attempted, rather the structural schemes of previous workers have been used as the basis for interpretation of the area.

The present aims of this thesis are threefold. Firstly, although the high grade metamorphism that produced the eclogites has been previously described, the retrogression of the Lewisian rocks and the relationships between deformation and retrogression have not been described. Sanders (e.g. 1972) described the eclogites in detail, but only the occurrence of fresh eclogite and not it's retrogressed equivalent, or the alteration of quartz - feldspar - kyanite streaks that cut across the eclogite. In many of his papers detailed observations of chemistry and textures were not related to the wider context of the entire inlier or its history. The textures of the retrogressed equivalents of the eclogites were described by Alderman (1935) but were not put into their tectonic context. The petrology of the Eastern Lewisian eclogites is therefore discussed prior to describing in detail their retrogression, to show that different eclogites types have undergone a similar history to each other and to the other rock types of the Lewisian. This history has been tied into a structural history based upon that of May *et al.* (1993). This necessarily repeats some of the work of Alderman (1935) and Sanders (1972, 1988, 1989) in order to establish a history of the eclogites to which that of other rock types and, more importantly, the Western Lewisian, may be compared. The petrology and chemistry of the other rocks of the Eastern Lewisian are then described. Much of this work confirms the conclusions of earlier workers, but includes important new observations on the relationships between nodules contained within the marble, hitherto undescribed, and the eclogites.

Secondly, the Western Lewisian rocks south of Loch Duich have not been described, other than in passing by Ramsay (1959) when discussing the structural history of the rocks, thus the petrology and chemistry are described in detail for the first time, and interpreted in order to construct a history of these rocks for comparison with the Eastern Lewisian and with the main foreland Lewisian outcrop.

Thirdly, the age of the eclogites remains open to doubt. Radiometric dates suggest a Grenville age of metamorphism whilst field evidence suggests a Scourian age. It is suggested after Mezger *et al.* (1992) that Sm - Nd dates using garnets are unreliable for rocks that have suffered multiple metamorphism above 600°C thus field and petrological evidence is preferred and compared to other metamorphic terrains, in particular the Grenville of Canada and the Scourian of NW Scotland. Further age data was to be added to that already published but unfortunately, although Sm, Nd, Rb and Sr concentrates from garnet and pyroxene separates from eclogites were prepared 20 months ago, these have not yet been run at East Kilbride and hence cannot be included in this thesis. Rb - Sr dates would have added a further dimension to the interpretation of Sm - Nd dates because of their lower closure temperatures.

Chapter Two

Geographical and Geological Setting

CHAPTER 2

Geographical and Geological Setting

2.1 Introduction

The northwest Highlands of Scotland are made up of basement gneisses (the Lewisian), foreland sediments (the Torridonian) and Cambro - Ordovician sediments, overwhich have been thrust a thick sequence of metasediments, the Moine, along the Moine thrust. Within the Moines are areas of metamorphosed igneous and sedimentary rocks that are similar in appearance to the Lewisian rocks of the foreland and which are interpreted as being inliers of Lewisian (e.g. Harrison and Moorhouse, 1976), but that have been metamorphosed and deformed along with the Moine rocks (e.g. Sutton and Watson, 1962), Figure 2.1. The largest of these inliers, the Glenelg inlier, is the subject of this thesis.

2.2 Geographical setting

The Glenelg inlier straddles the two peninsulas north of Knoydart between Loch Hourn and Loch Carron, opposite the island of Skye on the West coast of Scotland. The bulk of the inlier occurs on the Glenelg peninsular. Glenelg is a small village situated on the west coast of this peninsular, at approximately 57° 15' N, 5° 40' W. The peninsular is bounded to the north by Loch Alsh, to the NE by Loch Duich, to the west by the Sound of Sleat and to the south by Loch Hourn. To the SE the peninsular is bounded by mountains up to a height of 1010 metres (3314') on The Saddle (figure 2.2). The Glenelg peninsular is entirely situated on OS 1:50,000 map sheet 33, in area 'NG'. The geology is covered by BGS 1:50,000 sheets for Scotland 71E and 72W. The northernmost parts of the inlier, on the south coast of Loch Carron are on OS 1:50,000 sheets 24 and 25, and on BGS sheets 81E and 82W.

The high mountains bounding the Glenelg peninsular to the SE consist of good outcrop of the Morar group of the Moine. The Lewisian rocks occupy the lower ground

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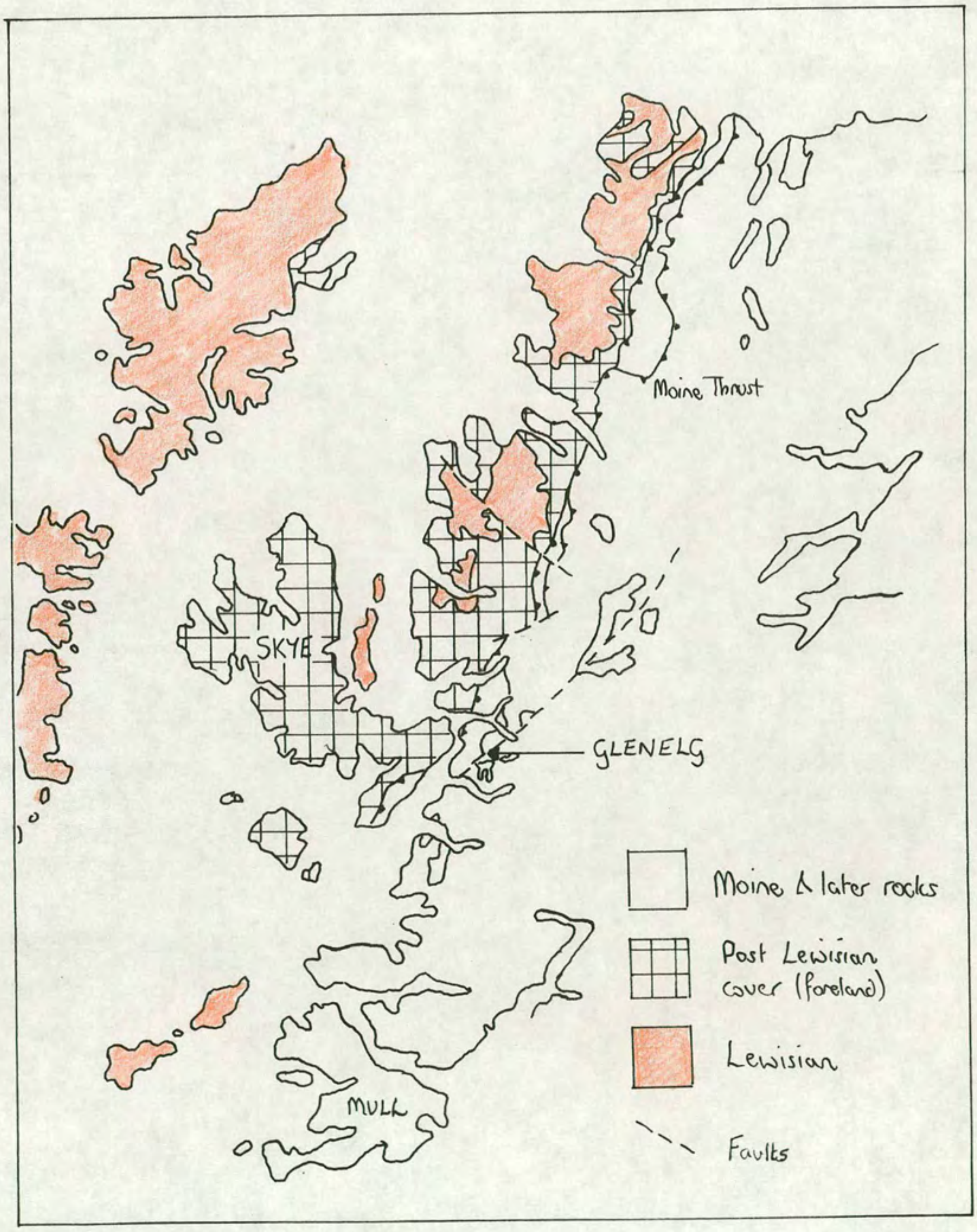
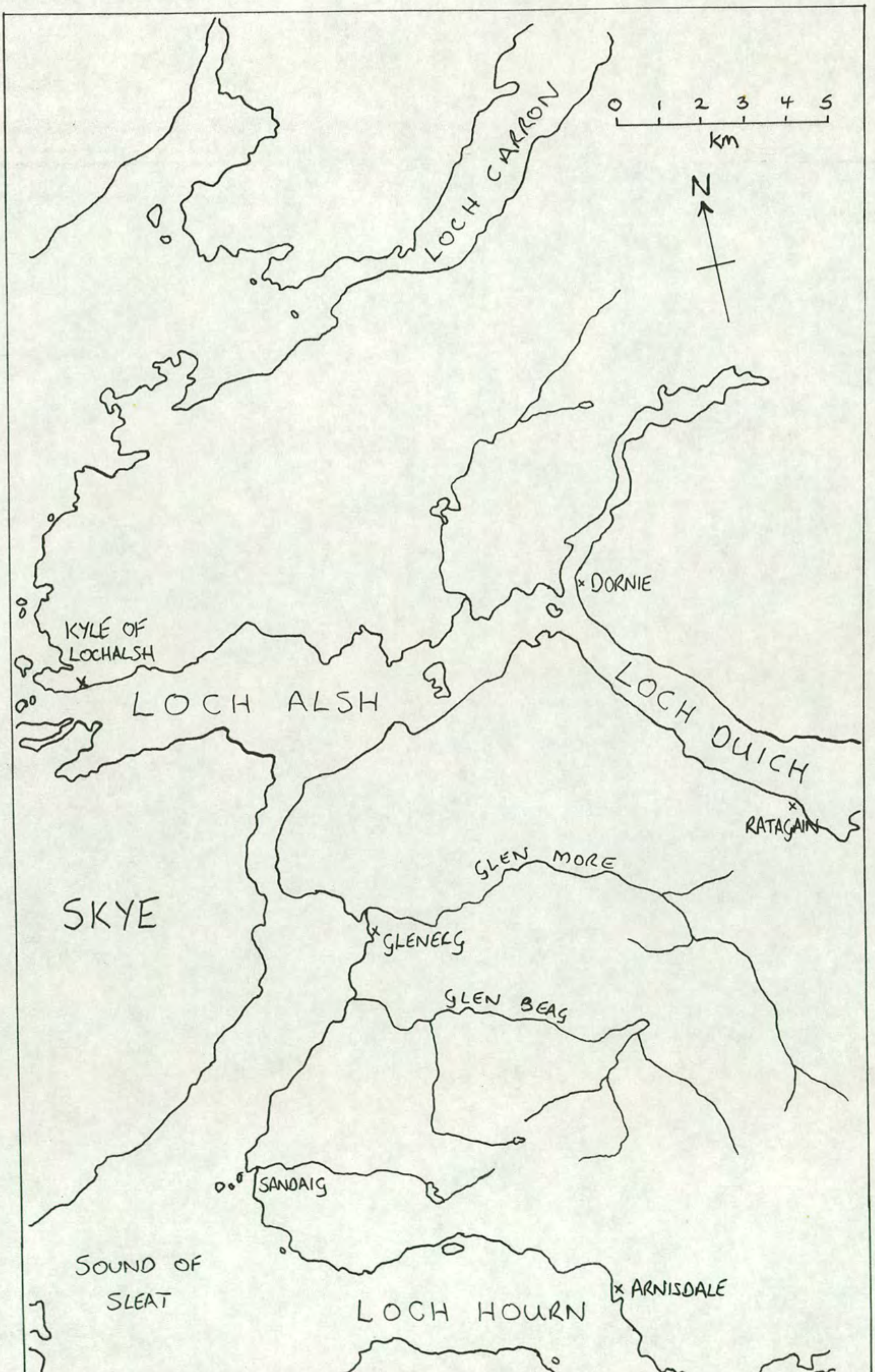
Figure 2.1 (following page) : Simplified geological map of Northwest Scotland

Figure 2.2 (second page) : Geography of the Glenelg peninsular


Moine Thrust
SKYE
GLENELG
MULL
Moine & later rocks
Post Lewisian cover (foreland)
Lewisian
Faults


0 1 2 3 4 5
km
N
LOCH CARRON
DORNIE
KYLE OF
LOCHALSH
LOCH ALSH
LOCH DUICH
RATAGAIN
SKYE
GLEN MORE
GLENELG
GLEN BEAG
SANDAIG
SOUND OF
SLEAT
LOCH HOURN
ARNISDALE

between these mountains and the sea, comprising land between 200 and 400 metres high, mostly covered by heather moorland and peat bogs, with poor exposure. This moorland is cut by two deep, steep - sided, glacial valleys running east - west, the Glen More to the north and the Glen Beag to the south. Exposures on the coasts of Loch Duich and Loch Hourn are good, but the coasts of Loch Alsh and the Sound of Sleat are predominantly coarse boulder beaches. About 20% of the peninsular is covered by forestry commission pine forest.

To the north of the Glenelg peninsular, Lewisian rocks are found east of Loch Duich and north of Loch Alsh, on similar ground to that of the Glenelg peninsular, with the Moine occupying higher ground and the Lewisian lower ground. South of the sound of Sleat Lewisian rocks occur in a narrow coastal strip along the east coast of the Island of Skye.

2.3 Regional geology

The geology of the Lewisian complex is summarised in Watson (1975). The foreland Lewisian rocks consist predominantly of intermediate and acidic rocks containing bands and pods of supracrustal rocks with some associated basic and ultrabasic material. The acidic rocks are typical of those found in many Archean cratons, formed from the partial melting of a mafic source under upper mantle conditions (e.g. Tarney and Weaver, 1987a). The acid and intermediate gneisses are characteristically depleted in mobile elements, such as K, Rb, Nb, Th and U (Tarney *et al.*, 1972). The early rocks are cut by felsic sheets that Rollinson (1994) suggests were intruded after initial metamorphism but prior to granulite facies metamorphism. The Lewisian rocks have been metamorphosed on two occasions during the Scourian, firstly at high pressure and temperature, 12 - 15 Kb, 1000°C (Barnicoat, 1983), then again at lower pressure and temperature, 10 - 14 Kb, 800 - 900°C (Savage and Sills, 1980). These two events are termed the Badcallian and the Inverian respectively, dated as approximately 2700 Ma and 2500 Ma old respectively, Cartwright and Valley (1992) suggest that metamorphism occurred under dry conditions with little fluid flow. Both Cartwright and Barnicoat (1989) and Kinny and Friend (1994) suggest that there may only have been one prolonged metamorphic event ending at 2500 Ma, the latter using isotopic evidence from zircons. These rocks were intruded after metamorphism by a series of basic and ultrabasic dykes, the Scourie dykes, which cut across fabrics within the gneisses. Over large areas both the gneisses and the intruded dykes have been deformed and metamorphosed at amphibolite facies during the Laxfordian, about 1700 - 1500 Ma, although Cliff *et al.* (1983) suggested that locally the Laxfordian metamorphism reached granulite facies.

The Lewisian rocks were then exhumed and a series of sediments, the Torridonian were deposited upon them. Meta - sediments of the Moine, which only occur east of the Moine thrust, possibly represent the metamorphosed equivalents of the Torridonian, and are also interpreted as having been deposited onto eroded Lewisian basement, e.g. Peach *et al.* (1910).

The Moine rocks have suffered a complicated series of metamorphic and deformational episodes. Interpretation of the events that have affected these rocks is hampered by difficulty in establishing a regional stratigraphy, because different parts of the Moine are separated by structural breaks, and by difficulty in correlating deformation events across large areas. The rocks are generally accepted to consist of three groups of rocks, the Morar, Glenfinnan and Loch Eil divisions, with each possibly being younger than the previous, although there is debate over the relative ages of these groups. For instance, Holdsworth *et al.* (1987) suggest that the topmost Morar group equates with the lowermost Glenfinnan group, whereas Piasecki and Van Breeman (1979) suggest that the Glenfinnan group might represent basement to the Loch Eil group and possible also the Morar group. The timing of deformation within the Moine is often defined by the ages of various intrusions into the different groups prior to different deformation events, thus the stratigraphic sequence and structural relationships between different areas are extremely important in understanding the ages of the rocks.

The Moine rocks are generally taken to have been metamorphosed and deformed prior to intense metamorphism and deformation during the Caledonian, 500 - 400 Ma, during which event peak pressures and temperatures increased from epidote - amphibolite facies in the west to upper amphibolite facies in the east. The age of the pre - Caledonian metamorphism and the number of deformation events to have affected the rocks is the subject of considerable debate, with anything but general discussion being beyond the scope of this thesis, except in so far as the age and conditions of metamorphism within the Moine conflict with the contention of Sanders *et al.* (1984) and Sanders (1989) that the Glenelg eclogite is ≈ 1000 Ma (Grenville), and metamorphosed at 750°C, 17 Kb. Powell *et al.* (1981) and Roberts and Harris (1983) suggest that the entire Moine sequence was metamorphosed at 1000 Ma (Grenville) prior to the Caledonian, citing Brook *et al.* (1976, 1977). However others suggest that early metamorphism cannot have occurred earlier than a 'Morarian' event at ≈ 750 Ma (e.g. Rogers, pers. comm.) by dating pegmatites that cut deformed Moine rocks, thought to have been intruded during the peak of metamorphism. In the east of the Moine outcrop there is thought to be one deformation event prior to the Caledonian deformation events, whilst in the west there are considered to be at least two, compounding problems of correlation across the Moine rocks (May *et al.*, 1993). The peak of metamorphism is often not clearly defined in the literature, but only referred to within broad facies definitions. However, Strachan and Treloar (1985) suggest that the Moine at Glenelg could have been metamorphosed at about 650 - 700°C, 6 - 8 Kb, whilst just to the east of Glenelg, at Kinlochhourn, Tanner (1976) suggests that the Moine was metamorphosed to at least 750°C, 8 Kb during the Caledonian.

Inliers of Lewisian within the Moine have been dated as Scourian, in particular the Scardroy inlier (Moorbath and Taylor, 1974). These inliers consist of banded acidic and basic rocks with some metasediments, in particular marble, now mostly retrogressed to amphibolite facies, and are characteristically cut by basic dykes (e.g. Watson, 1975). The inliers are mostly found close to the Moine thrust, as is the case at Glenelg, but also occur alongside other major structural breaks within the Moine, as is the case at Scardroy (Sutton and Watson, 1962) which occurs alongside the Sgurr Beag slide.

2.4 The Glenelg inlier

The Glenelg inlier is bounded to the west by the Moine thrust and to the east by the main outcrop of the Moine. To the SE the inlier is cut by the Strathconon fault, of Caledonian age. Alongside Loch Duich the inlier is cut by the Ratagain intrusion, also of Caledonian age. The inlier consists of alternating strips of Moine and Lewisian rocks which extend roughly parallel to its length. East from the Moine thrust is a thin strip of Moine rocks, then two areas of Lewisian rocks separated by a strip of highly deformed Moine and Lewisian rocks. The Lewisian rocks either side of this strip have distinctly different characteristics and are termed the Eastern and Western Lewisian (Ramsay, 1957) (see Figure 2.3). The Western Lewisian consists of migmatitic and granodioritic acid gneisses and a variety of basic rocks including pyroxene - granulite and hornblende - schist north of Loch Alsh (Barber and May, 1975). Eclogite occurs in one exposure, south of Loch Alsh. The Eastern Lewisian is much more variable, containing common eclogite

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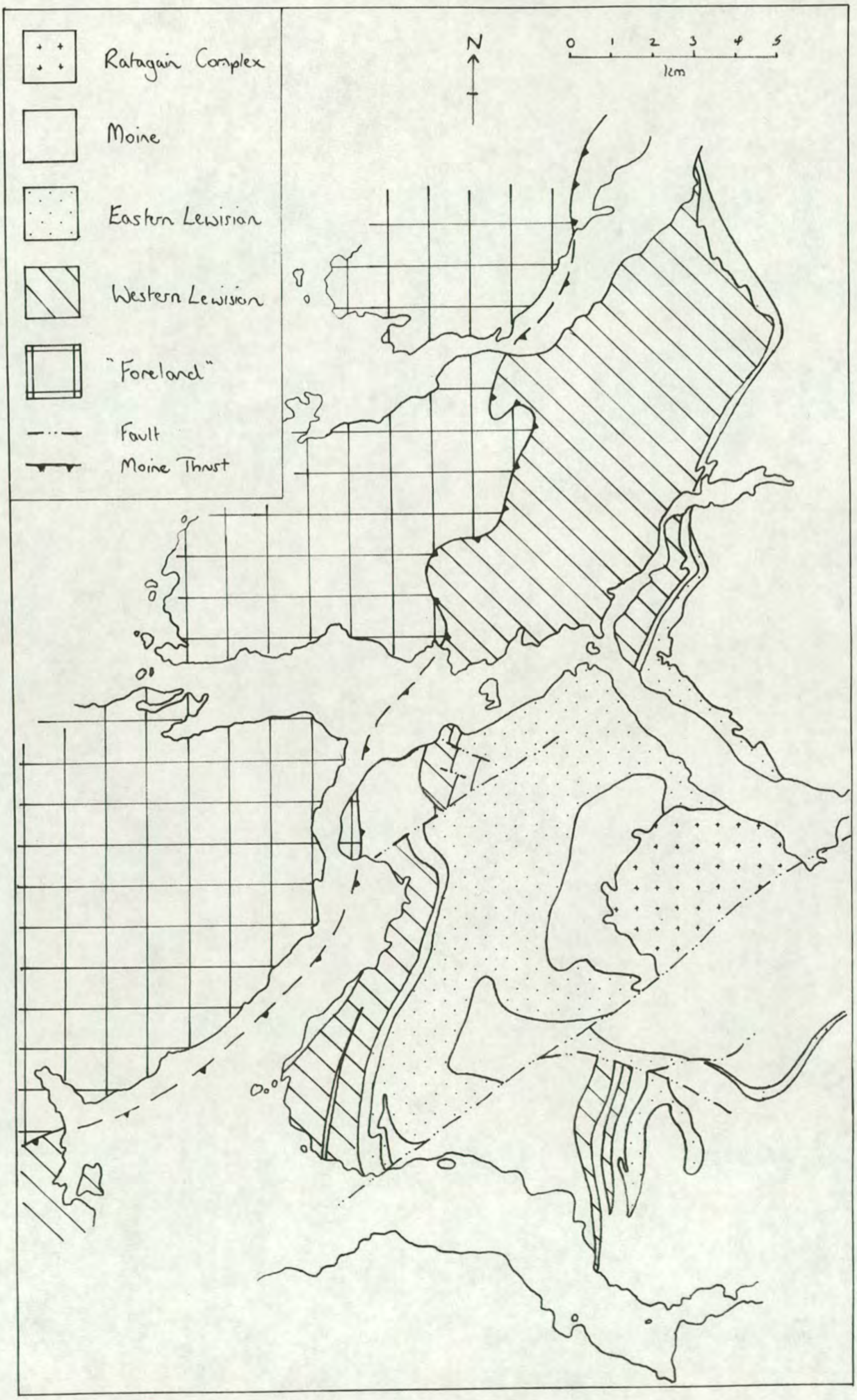
Figure 2.3 (over page) : Sketch map of the general geology of the Glenelg inlier and surrounding areas.



Ratagain Complex
Moine
Eastern Lewisian
Western Lewisian
"Foreland"
Fault
Moine Thrust
N
0 1 2 3 4 5
km

as well as ultrabasic rocks and a wide variety of metasediments, including olivine - marble, garnet - biotite - kyanite gneiss, eulysite, graphitic schist and calc - silicates. Moine rocks overlie both Western and Eastern Lewisian rocks unconformably, with a locally - developed basal conglomerate (Peach *et al.*, 1910) which passes up into a basal pelite, the base of the Morar group of the Moine, and then into psammites and pelites (Ramsay and Spring, 1962).

Work on the area is based upon the results of fieldwork undertaken by the British Geological Survey, published as a report of the geology of Scottish map sheet 71 (Peach *et al.*, 1910). The work was mainly that of Clough who described in detail the field occurrence of both the Lewisian and the Moine rocks.

2.4.1 Structural geology

The structural history of the Glenelg inlier and the western portion of the Moine nappe was summarised by Ramsay (1963) and updated by May *et al.* (1993). The detailed structural work on the area was published by Ramsay (1958) and Sutton and Watson (1958), in which Ramsay mapped the area south of the Glen More of Glenelg, and Sutton and Watson mapped that to the north. Barber and May (1975) mapped the area between Loch Alsh and Loch Carron to the north of Glenelg. Thin Lewisian sheets within the Moine immediately to the east of Glenelg were recorded by Clifford (1955) and Simony (1973). These papers collectively identified four main deformation events that affected the Moine and Lewisian rocks together.

Ramsay (1958) initially suggested that the Moine and Lewisian rocks were thrust together and folded, producing a strong fabric seen throughout the area and two large folds with NE striking, east dipping axial planes. Accompanying this deformation was recrystallisation of the Moine and Lewisian and the intrusion of pegmatites. A second folding event produced a new major fold with a SE - dipping axial plane and SE - plunging hinges. Ramsay also noted that the degree of deformation was highly variable and that it was greatest in the Eastern Lewisian and least in parts of the Western Lewisian where cross - cutting relationships between various groups of rocks could be still be seen. Deformation was also often concentrated in intensely deformed narrow zones at the margins of lithological types, especially the basic rocks. Later re - interpretation (Sutton and Watson, 1958, Ramsay, 1963) made the first and second of Ramsay's deformation events D_2 and D_3 respectively.

The D_1 event was recognised as producing a strong fabric in rocks throughout the area accompanied by some foliation - parallel isoclinal folding, although the exact nature of the first event has been open to much speculation. Sutton and Watson (1958) suggested that because there was no repetition of Lewisian rock types with respect to the Moine the two rock types must have been initially thrust together, however they and Ramsay (1963) suggest that large scale plastic deformation must have occurred to remove original unconformities existing between the Moine and the Lewisian, and possibly within the Lewisian itself. This event is thought by May *et al.* (1993) and by previous workers to have been pre - Caledonian.

The D_2 deformation produced tight folds, folding the D_1 fabric. In places a new axial planar foliation occurred and strong linear features were produced parallel to the axial planes of folds. May *et al.* (1993) interpret this D_2 deformation as being the first Caledonian event to affect the rocks, and suggested that brittle deformation also occurred along a number of slides, in particular the Central Moine Strip, and that the Eastern Lewisian and overlying Moine rocks were thrust onto the Western Lewisian at this time. Sutton and Watson (1958) map out a number of 'zones of cataclasis', both within the Eastern and Western Lewisian, and the 'central Moine strip' between them. The D_2 event occurs either immediately after, or along with, the peak of metamorphism. It is suggested by May *et al.* (*op cit.*) to be Caledonian in age, although previous workers, principally Ramsay (1957), thought it to be pre - Caledonian.

The D_3 deformation was the last major deformation event, and all folds associated with it tend to strike NE - SW. These folds tend to be gentle open folds refolding the earlier structures. The D_4 deformation produces cracks and microfaults in all the rocks, lessening with distance from the Moine thrust. All previous workers agree that these events (i.e. D_3 and D_4) are of Caledonian age.

Two problems arise from this interpretation of the structural history of the area. Firstly there is no recognised deformation event related to the uplift of either the granulites of the Western Lewisian or the eclogites of the Eastern Lewisian prior to Moine deposition. This may be because the high - grade rocks preserved at present have escaped previous deformation whilst their deformed equivalents have had any textural details of this uplift obliterated by intense later deformation. Alternatively it may simply be the case that no one has, as yet, looked for such a deformation, or that there is no deformation phase required because the Moine was not actually deposited on the Eastern Lewisian and metamorphism of one occurred synchronously with metamorphism of the other. It is also possible that movement along the central Moine strip has re - activated already mylonitised rocks related to the exhumation of the eclogites, although all previous workers suggest that the central Moine strip contains both Moine and Lewisian rocks and thus, in its present state, it must postdate Moine deposition. Secondly the structural sequence of May *et al.* (1993) shows events in the Western Lewisian, post Moine deposition, that do not correlate with the Eastern Lewisian and overlying Moine. If the correlations are true, it implies that there is a widespread early Moine deformation event involving intense plastic deformation that interleaved the Moine and Lewisian rocks, followed by localised folding only seen in the Western Lewisian only. It is interesting to note also that Barber and May (1975) found it possible to relate structures in the Moine and Western Lewisian north of Loch Alsh with the structural sequence of Ramsay (1963), whilst May *et al.* (1993) have re - interpreted these structures in the light of re - mapping and find no correlation; also Barber and May (1975) state that the structural history of the Western Lewisian rocks (north of Loch Alsh) was only interpreted by studying the surrounding Moine rocks and following structures into the Lewisian.

A summary of the history of the Western and Eastern Lewisian and surrounding Moine as suggested by May *et al.* (1993) after previous authors is given in table 2.1. Throughout this thesis the sequence of events D_1 - D_4 suggested by May *et al.* (1993) for the Eastern Lewisian and Moine rocks have been adopted as the structural sequence, without any speculation as to the absolute ages of these deformation events. Thus D_1 is taken to be an event that involved isoclinal folding and interleaved Moine and Lewisian, and thus has to be post - Moine in age. D_2 was a complicated event syn - or immediately post the peak of amphibolite facies metamorphism, in which both folding and sliding occurred, with the formation of a number of discrete slide zones within the Moine and the Lewisian, including the central Moine strip. D_3 was a period of intense folding, and further sliding, including the Moine thrust. D_4 involved some small scale folding, thought by Sutton and Watson (1958) to be due to further movements along the Moine thrust.

2.4.2 The origin and metamorphic history of the eclogites and related rocks of the Eastern Lewisian.

The earliest workers on the Glenelg rocks concentrated on describing the petrology of a number of unusual rocks found in the area. Alderman (1935) described the eclogites in some detail, recognising that much of the basic amphibolite facies gneiss of the Eastern Lewisian was once eclogite. Read and Double (1935) described the marbles

Glenelg (structure) (after Ramsay, 1963)	**Western Lewisian** (after Barber & May, 1975; May *et al.*, 1993)	**Eastern Lewisian** (after Barber, 1968; May *et al.*, 1993)	**Moine** (after May *et al.*, 1993)
	Migmatites	Migmatites	
	Intrusion of granodiorite		
	Intrusion of basic rocks	Intrusion of basic rocks	
		Deposition of sediments	
	Granulite facies met.	Eclogite facies met.	
	Intrusion of dykes	Possible int. of basic dykes	
Deposition of Moine	Deposition of Moine	Deposition of Moine	Deposition of Moine
D_1 : interleaving of Moine & Lewisian	D_1 : interleaving of Moine & Lewisian	D_1 : interleaving of Moine & Lewisian	D_1 : interleaving of Moine & Lewisian - isoclinal folds
D_2 : tight folds, ESE lin	D_2 : further interleaving		
	D_3 : SE plunging folds		
Amphibolite facies met.	Amphibolite facies met.	Amphibolite facies met.	Amphibolite facies met.
	D_4 : mylonites & ESE lin.	D_2 : folding & mylonites	D_2 : folds (ESE lin.) & slides
D_3 : SE plunging folds	D_5 : folding	D_3 : folding	D_3 : SE plunging folds
	D_6 : monoclinal folds	D_4 : monoclinal folds	

and Tilley (1936, 1937, 1938a) the eulysites and some kyanite - bearing eclogites. Sutton and Watson (1958) emphasised that the Western Lewisian resembled the foreland Lewisian with acid and basic gneisses cut by late discordant basic dykes, whilst the Eastern Lewisian was potentially different.

Later work on the area concentrated almost exclusively on the age and origin of the eclogite within the Eastern Lewisian and its relationship to the other Eastern Lewisian rocks. Alderman (1935) suggested that the eclogite was almost certainly produced from metamorphism *in situ.*, Mercy and O'Hara (1968) suggested that most of the eclogites were of suitable composition to have been Scourian rocks. However, some eclogites, such as a nepheline - normative eclogite, were possibly produced by crystallisation of alkali - basalt magma at depth. Sanders (1972) also suggested that whilst most eclogites were probably produced *in situ.* due to the similar pressures and temperatures of metamorphism calculated for both the eclogites and the metasediments, an Al - Ti - pyroxenite might also represent crystallisation of some new basic material during high grade metamorphism.

Sanders (1972) provides the framework for the petrology of the Eastern Lewisian parts of this thesis. The main points are summarised in Sanders (1988, 1989). Sanders (1972) suggested that three sorts of eclogite existed, metabasites represented by orthopyroxene - eclogite, metatholeiites by 'normal' garnet - clinopyroxene eclogite and metagranite by garnet - clinopyroxene - quartz - feldspar rocks. Representative mineral analyses were published. He noted in particular the change in X_{Ca} of garnet from being lowest in orthopyroxene eclogite and highest in so - called metagranite. It was suggested that the lack of zoning within minerals and the differences in mineral composition within single samples of eclogite was because they remained dry rocks, both during and after metamorphism, although there were two periods of garnet growth. Evidence was presented for other rocks within the Eastern Lewisian being metamorphosed under similar conditions to the eclogites, which suggests that the bulk of the eclogites were metamorphosed *in situ.* The conditions of formation of the eclogite were summarised and some of the retrogressive changes to the rocks were described. Quartz - kyanite - feldspar streaks that occur within the eclogite were thought to be due to plagioclase rich patches in the original rock.

Sanders (1988) presented a detailed analysis for the reactions occurring within and alongside kyanite - bearing streaks within the eclogite. He estimated an initial eclogite facies event occurred at 700°C,>14 Kb, followed by prograde metamorphism to 750

°C,>17 Kb, recorded at the rims of quartz - plagioclase - kyanite streaks by the growth of Ca - rich garnet, formed from the breakdown of anorthite, whilst albite formed jadeite rich pyroxene. Deformation and retrograde metamorphism produced aligned kyanite needles within the streaks and rim of oligoclase on kyanite. The conditions were estimated to be 750°C,>15 Kb. Sanders (1989) estimated the initial conditions of formation of the eclogite and surrounding rocks to be approximately 730°C,>16 Kb, on the basis of garnet - pyroxene thermobarometry for the eclogites, coexisting calcite and dolomite compositions within the marbles, and using garnet - plagioclase - kyanite - quartz barometry for quartz - feldspar - kyanite streaks within the eclogite. Manning and Bohlen (1991) used the data from Sanders (1988) to check calibration of a sphene - kyanite - anorthite - rutile barometer and (not surprisingly!) obtained similar pressure conditions for the rocks.

Barber (1968) described the Eastern Lewisian rocks east of Loch Duich and interpreted them as having been a migmatite complex prior to the intrusion of basic rocks and then the deposition of sediments, all prior to eclogite facies metamorphism. Although no actual cross - cutting relationships were seen, he also suggested the possible presence of later dykes that did not suffer the high - grade metamorphism, but were affected by later deformation and hence intruded prior to the deposition of Moine sediments.

2.4.3 The origin and metamorphic history of the Western Lewisian rocks.

Barber and May (1975) detailed the history of the Western Lewisian rocks north of Loch Alsh. They established that the Western Lewisian had a comparable history with the foreland Lewisian. They suggested that a migmatite complex was intruded by granodioritic rocks, then basic rocks prior to high grade metamorphism that produced granulite facies gneisses. The area was then intruded by a suite of basic dykes that show no evidence for high grade metamorphism. The Moine sediments were deposited onto the exposed Western Lewisian rocks. The whole area was then repeatedly deformed, and was metamorphosed to the amphibolite facies. Four deformation events were identified, affecting both the Lewisian and Moine rocks, although later events did occur in the Moine. The last of these four events included movement along the Moine thrust and along the central Moine strip.

2.4.4 Age of the rocks of the Glenelg inlier.

Barber and May (1975) suggested that a single occurrence of eclogite within the Western Lewisian south of Loch Duich might be of similar age to the granulite facies metamorphism north of Loch Duich, but representing slightly different conditions of metamorphism. Moorbath and Taylor (1974) dated rocks from the Western Lewisian south of Loch Duich as being of possible Scourian age, obtaining K - Ar ages of 2200 - 1600 Ma. Cliff (pers. comm.) dated sphenes from the Western Lewisian eclogite at around 1200 Ma. Sanders (1979) mentions the occurrence of eclogite in the Western Lewisian and suggests that it is of post Scourie dyke age because both the eclogite and a basic dyke within the Western Lewisian are basalts of similar composition.

Ramsay (1958) and Sutton and Watson (1958) both thought from field evidence that the eclogite of the Eastern Lewisian was probably of Scourian age. Radiometric dating on the eclogites was first done by Miller *et al.* (1963) who produced K - Ar ages of 1515 ± 104 Ma and tentatively suggested a Laxfordian history for the eclogite. Sanders *et al.* (1984) published two Sm - Nd ages for the eclogite of 1082 ± 24 Ma and 1010 ± 13 Ma and suggested that the eclogites were therefore formed during the Grenville orogeny. These dates of Sanders *et al.* are in conflict with dates for the Moine of Brook *et al.* (1976, 1977) of 1024 ± 96 Ma, interpreted as the peak of Moine metamorphism, syn - or immediately post - D_2 regional deformation, also the peak of post - eclogite facies metamorphism within the Lewisian of the inlier, although it is possible that eclogite facies metamorphism occurred prior to D_1 and D_2 but that all occurred within a relative short period of time around 1000 Ma. The work of Mezger et al. (1992) casts doubt on the validity of dates produced by Sm - Nd on garnets by demonstrating that garnets only a few cm across, such as those in Glenelg, will not conserve the age of early metamorphism if re - metamorphosed at above $\approx 600°C$.

There seems little doubt that the Western Lewisian can be correlated with the Scourian of the foreland Lewisian, although the reason for the occurrence of eclogite within the Western Lewisian in the south of the inlier is open to debate. Whilst counterparts of the wide variety of rocks found in the Eastern Lewisian are found in the foreland Lewisian, especially on South Harris, and the rocks are almost certainly Lewisian in origin, the age of the eclogite facies metamorphism is open to doubt. The age of formation of the eclogites in the Eastern Lewisian is generally taken to be ≈ 1050 Ma, following the suggestion of Sanders *et al.* (1984). However, there is some (scant !) evidence within the Eastern Lewisian to suggest that it may have suffered a similar history to the Western Lewisian, primarily the presence of possible basic dykes that have not been metamorphosed at high pressure and temperature (Barber, 1968; May *et al.*, 1993), and thus the whole issue of the age of both the Western and Eastern Lewisian, and of the age of early metamorphism of the Moine, is called into question. The most likely possibilities for the relative ages of the eclogites within the Eastern Lewisian and the granulites within the Western Lewisian are :

A: The Western Lewisian granulites are Scourian, the Eastern Lewisian eclogites are Grenville, metamorphosed at ≈ 1000 Ma prior to the deposition and subsequent deformation and metamorphism of the Moine and re - working of the Lewisian at ≈ 750 Ma (as suggested by Sanders *et al.*, 1984).

B: The Western and Eastern Lewisian high grade rocks are both Scourian and both groups of rocks have suffered a similar history, with deformation and metamorphism of the Moine and re - working of the Lewisian at ≈ 1000 Ma.

C: The Western Lewisian granulites are Scourian, the Eastern Lewisian eclogites represent Grenville basement (> 1450 Ma), the Moine was deformed and metamorphosed and the Lewisian re - worked at ≈ 1000 Ma.

D: The Moine was not deposited onto the exposed Eastern Lewisian, rather Grenville age metamorphism at ≈ 1000 Ma affected both the Eastern Lewisian and the Moine synchronously, with the Lewisian buried deeper than the Moine. The two groups of rocks were subsequently bought together during deformation at ≈ 1000 Ma in D_1.

The validity of each of these possibilities will be discussed in the conclusions.

PART TWO
The Eastern Lewisian

Chapter Three

Field description of the Eastern Lewisian rocks

CHAPTER 3

Field description of the Eastern Lewisian rocks

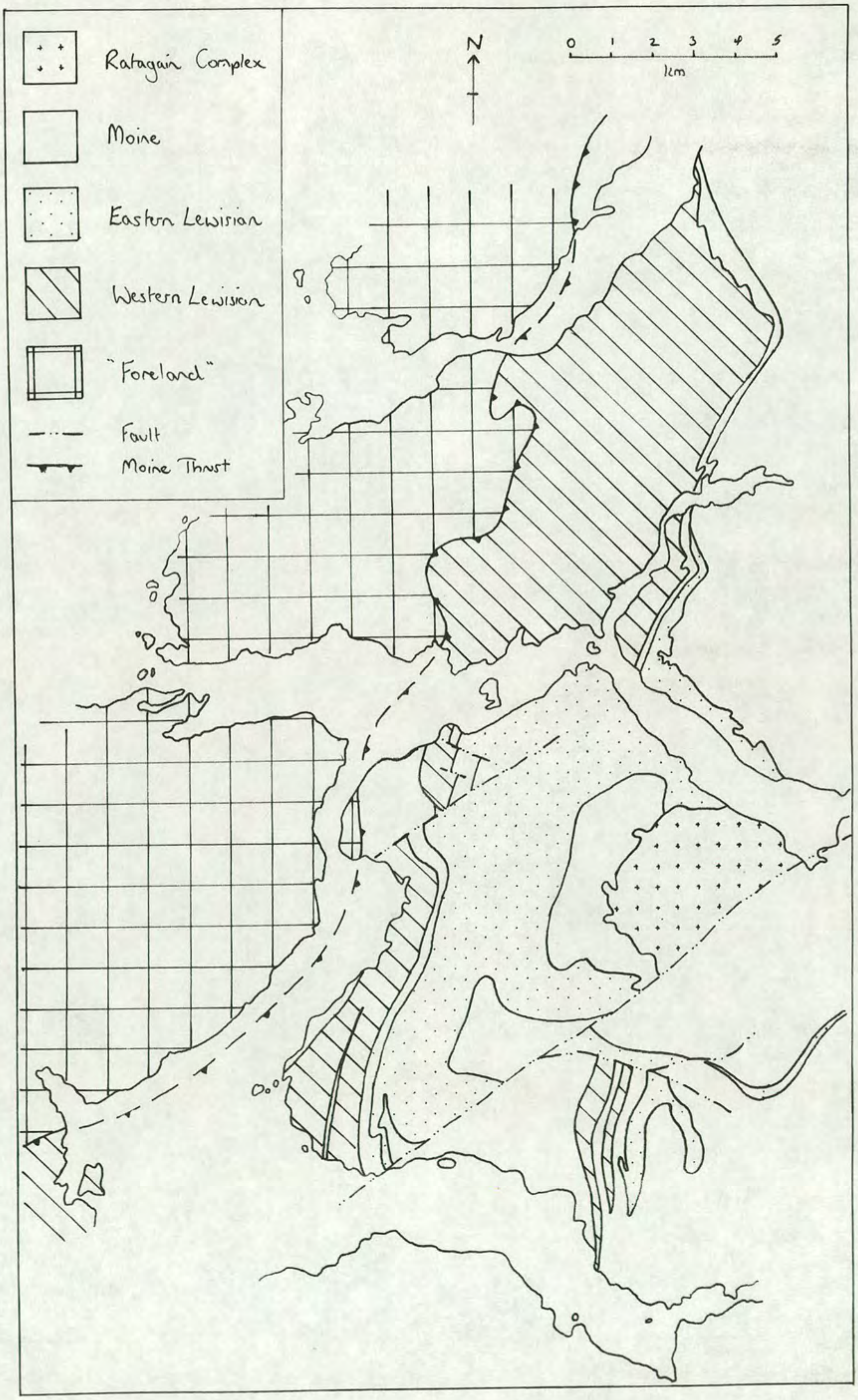
3.1 Introduction

3.1.1 Introduction

In this chapter the field relationships of the Eastern Lewisian rocks are described and interpreted. Figure 3.1 shows the distribution of these rocks. The largest outcrop of Eastern Lewisian rocks occurs in a strip up to 5 km wide and 15 km long running from Loch Long in the north Loch Hourn in the south. To the north the strip is pinched out between two outcrops of Moine rocks, which otherwise bound the strip to the east and west. The eastern outcrop is the main Moine outcrop of the Highlands. The western outcrop is a thin, highly tectonised strip of Moine and Lewisian rocks separating the Eastern and Western Lewisian rocks. To the south the Eastern Lewisian strip is cut by the Strathconon fault, with further outcrops of both Western and Eastern Lewisian - type rocks occurring on the other side, near Arnisdale, 10 km to the SE of Glenelg. Other Eastern Lewisian - type rocks occur further east within the Moine (May *et al.*, 1993).

The rocks of the Eastern Lewisian are extremely varied, and are composed of a number of metamorphosed igneous and sedimentary rocks. The former include acid, basic and ultrabasic rocks, of which fresh basic rocks occur as eclogites and fresh ultrabasic rocks as websterites. The metasediments include olivine - marbles, calc - silicates, graphitic rocks, eulysites, kyanite - bearing pelites and quartzo - feldspathic rocks. Detailed descriptions of the eclogites may be found in Alderman (1935) and in Sanders (1972), and of the eulysites in Tilley (1936). Descriptions of all rock types can be found in the Geological Survey Memoirs (Peach *et al.*, 1910; May *et al.*, 1993). Barber (1963) and May *et al.* (1993) suggested that some basic and ultrabasic rocks within the Eastern Lewisian may not have been metamorphosed at eclogite facies and could represent dykes intruded into the Eastern Lewisian after that metamorphism. This is discussed further in chapter six.

Figure 3.1 (following page) : Sketch map of the general geology of the Glenelg peninsular and the surrounding area with the outcrop of Eastern Lewisian rocks highlighted.


Ratagain Complex
Moine
Eastern Lewisian
Western Lewisian
"Foreland"
Fault
Moine Thrust
N
0 1 2 3 4 5
km

Most of the work on the Eastern Lewisian rocks in this thesis has concentrated on the eclogites at three localities between Loch Duich and the Glen More of Glenelg. By looking in detail at these localities it is possible to identify a series of events that have affected the eclogites and thus to infer their metamorphic and deformation histories. The reason for studying the eclogites in more detail than the other rock types is that they have a simple, easily recognisable, anhydrous mineralogy which relates to a high pressure - temperature event and which has been partly preserved despite a number of later retrogressive events. This high grade event serves as a reference point from which to study these later events. The eclogites also tend to be better exposed than other rock types, although this often means that the shape of eclogitic bodies and contacts with other rock types are obscured, because contacts with other rock types are not seen.

For each of the three main localities the appearance of the eclogites and, where relevant, other rock types shall be described, although detailed field work, particularly the re - assessment of earlier structural interpretation, was beyond the scope of this thesis. At the end of the chapter the observations will be summarised and a geological history for the eclogites inferred, where possible indicating where other rock types have a similar or different history.

3.1.2 Locations of detailed outcrops

All three localities are between Loch Duich and the Glen More of Glenelg, shown in Figure 3.2 which shows the general geology of the area.

Loch Duich and the Glen More are both steep sided glacial valleys with little exposure on the valley sides, these being mainly grass and woodland. The land between these valleys ranges in height from 300 - 400 m, and is boggy with very poor exposure, although the eclogite and the marble tend to be consistently better exposed than other rock types. In particular two ridges of eclogite are well exposed. One occurs immediately SW of Lochan na Beinne Faide, around GR. 862236, the other occurs about 3 km SW, 100 m WSW of Loch Coire an Daimh, around GR. 842216. The former is the type locality for the eclogite described by Sanders (1972), essentially a bimineralic garnet - clinopyroxene

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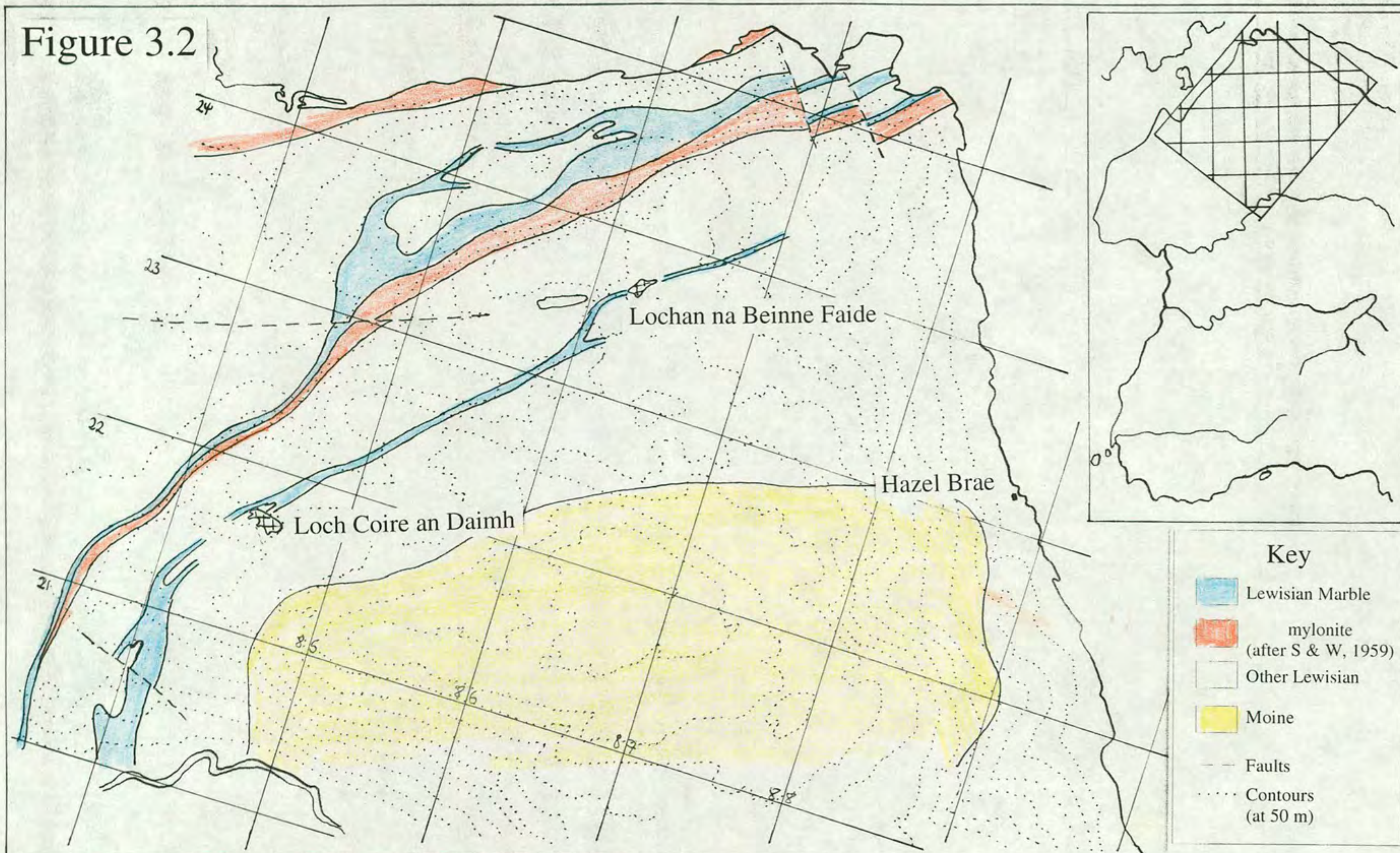
Figure 3.2 (following page) : Sketch map of the geology of the Eastern Lewisian between Loch Duich and the Glen More of Glenelg, after Sutton and Watson (1958), with modifications.

Figure 3.2


24
23
22
21
Lochan na Beinne Faide
Loch Coire an Daimh
Hazel Brae
85
86
87
88
Key
Lewisian Marble
mylonite (after S & W, 1959)
Other Lewisian
Moine
Faults
Contours (at 50 m)

rock. It is an excellent location in which to examine fresh eclogite, as well as to see most of the other rock types of the Eastern Lewisian. The latter locality is the type locality of Sanders (1988), and contains predominantly eclogite with variable quartz content, and areas rich in quartz - feldspar - kyanite bearing streaks. The other locality is on the south coast of Loch Duich, were exposure is reasonable, on a number of small headlands all along the loch. The outcrop to be described in detail extends for some 450 m from the cottage at Hazel Brae, GR. 887233 (marked on OS maps), to beyond Fern Villa at GR. 885235 (also marked on OS maps), the site of the original discovery of eclogite in Scotland by Teall (1891). This outcrop shows a variety of features already described for the above outcrops, but also shows the effects of late deformation on the eclogites and related rocks.

3.2 Lochan na Beinne Faide

Immediately SSW of Lochan na Beinne Faide (GR. 862236) is a prominent hill with its crest formed of well exposed eclogite. To the east of this hill the exposure is poor and the ground drops gently away to some small lochans with little exposure. To the west is a cliff of garnet - quartz - feldspar rock and marble. At the base of the marble are interleaved, sheared quartzo - feldspathic rocks, eclogite and amphibolite. Figure 3.3 is a sketch of the relationships at this locality. Further west is a grassy valley which the Geological Survey (Peach *et al.*, 1910) mapped as a fault. Beyond this valley the land rises to Beinn Fhada, which, for some 1 km across strike, consists of garnet - biotite - quartz - feldspar rock. Small red garnets, up to 4 mm across occur with biotite rims, as augen in a fine grained quartz - feldspar - biotite matrix.

The eclogite is a coarse grained bimineralic rock, with dark red garnets and pale green pyroxene, both up to 1 cm across. There is approximately 60% pyroxene and 40% garnet. Cracks filled with dark green amphibole are common, sometimes with a paler yellow centre of epidote and actinolite. These cracks are fairly continuous and are often up to 1 cm across, with the pale centres a maximum of 1 mm across (plate 3.1.A).

Within the eclogite there occur patches of coarser eclogite up to 20 cm across that are usually roughly spherical and slightly weathered into the rock face. These either consist predominantly of garnet, normally about 80% of the coarse grained area, with

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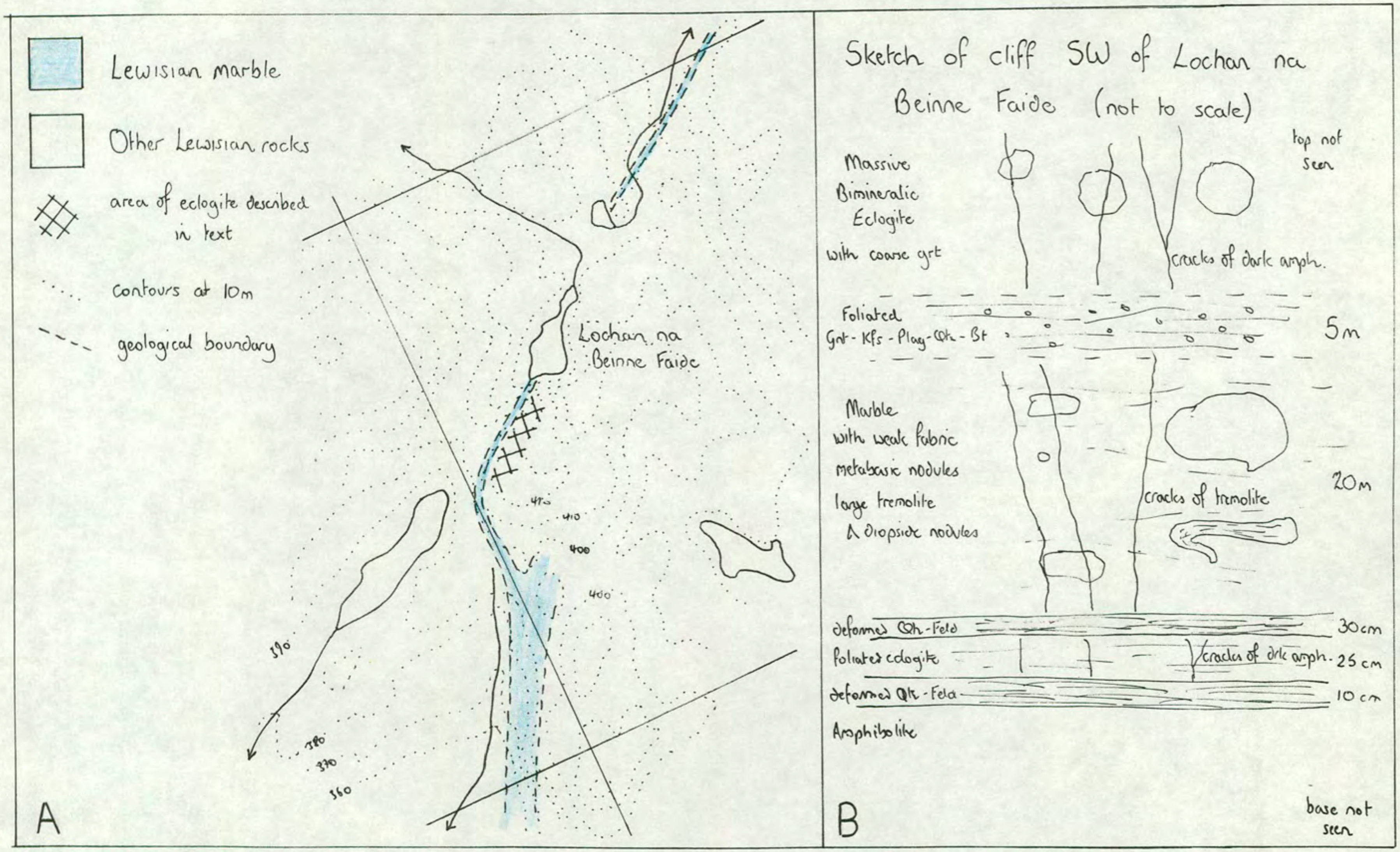
Figure 3.3 (following page) : Sketch section of the geology of the prominent cliff immediately SE of Lochan na Beinne Faide (GR 862236).


Lewisian marble
Other Lewisian rocks
area of eclogite described in text
contours at 10m
geological boundary
Lochan na Beinne Faide
410
410
400
400
390
380
370
360
A
Sketch of cliff SW of Lochan na Beinne Faide (not to scale)
top not seen
Massive Bimineralic Eclogite with coarse grt
cracks of dark amph.
Foliated Grt - Kfs - Plag - Qtz - Bt
5m
Marble with weak fabric metabasic nodules large tremolite & diopside nodules
cracks of tremolite
20m
deformed Qtz - Feld
30cm
Foliated eclogite
cracks of drk amph.
25 cm
deformed Qtz - Feld
10 cm
Amphibolite
base not seen
B

inclusions of pyroxene up to 2 cm across, or else are single, large, inclusion - free garnets (plate 3.1.B). These garnets are of a similar colour to the small garnets in the surrounding eclogite. The eclogite at the rim of these large garnets has no change in the relative proportions of pyroxene and garnet. Both these types of patch are cut by thin cracks filled with dark green amphibole.

Most of the eclogite at Lochan na Beinn Faide is fairly fresh, with no obvious alteration of pyroxene or garnet, although in places there are conspicuous small blebs of black amphibole, often as rims to garnets (plate 3.1.C). Some of the large single garnets are cut by cracks up to 1 cm across, filled with quartzo - feldspathic material. These cracks widen out to contain large crystals of black amphibole, up to 5 cm's across, with minor plagioclase and biotite (plate 3.1.D).

At the top of the cliff to the west of the eclogite and above a prominent marble band which forms most of the cliff, there is approximately 5 metres of varied garnet - biotite - quartz - feldspar rock. Close to the eclogite the rock consists of about 70% dark brown garnets up to 5 mm across, rimmed by black biotite. Close to the marble, the rock has little biotite, and consists of approximately 50% dark red garnets up to 5 mm across within dirty quartzo - feldspathic material. Between these, the rock has sparse pale pink garnets up to 4 mm across making up about 30% of the rock within a matrix of dusty feldspar and clear quartz. Throughout the rock the garnets occur as cracked augen within the quartzo - feldspathic material.

The rest of the cliff, some 20 m high, is formed of marble. Like all the marbles in Glenelg it weathers to a dark brown colour. It has a rubbly texture with silcate minerals standing proud, and contains roughly spherical nodules of serpentine, diopside and tremolite, often occurring in layers. The serpentine nodules are pale brown, generally small, up to 1 cm across, but sometimes form a rind up to 2 mm thick on the tremolite lumps. The diopside nodules are white and of variable size, up to a maximum of about 20 cm across and sometimes have a narrow rind of pale green fibrous amphibole. The tremolite nodules are white and of variable size, occasionally up to 1 metre across. These last nodules are usually rounded, but sometimes elongate. There is also a weak layering to the marble which wraps around these nodules (plate 3.2.A). Many of these features are described by Clough in the Survey memoir (Peach *et al.*, 1910). The marble is also cut by a number of veins. These are of variable intensity and, although there are few veins at Lochan na Beinn Faide, the rock is heavily veined in marble outcrops to the SW. These veins are of similar orientation to those in the overlying eclogite but are pale in colour, being filled by tremolite (plate 3.2.B).

In places the marbles contain nodules of basic rocks, up to 50 cm across. The outcrop at Lochan na Beinne Faide is particularly rich in nodules, most of which can easily be correlated with basic rocks throughout the Eastern Lewisian. It may be significant that there are no recognisable nodules of any metasedimentary rock types. There are nodules of calcite - bearing eclogite; garnet - biotite - amphibole - quartz - feldspar rock, which is probably a result of eclogite alteration; altered ultrabasic pyroxenite; and pyroxene - rich eclogite. The most unusual nodule is an elongate mass some 2 m long of mylonitised garnet - biotite - orthopyroxene - clinopyroxene - quartz - feldspar rock with a strong lineation that has been folded along with the marble (plate 3.5.A). A second unfolded nodule of the same material occurs close by. These nodules are of great importance in understanding the history of the area because they do not correspond to any of the rocks identified outwith the marble and, although they share many textures with the eclogites, they also display textures and mineral associations not seen in them. These nodules will be described further in chapter six.

The base of the marble can be seen in one small outcrop at the base of the cliff. It rests upon 30 cm of sheared quartzo - feldspathic material, which in turn rests upon 25 cm of foliated eclogite with quartz, itself sitting on a further 10 cm of sheared quartzo - feldspathic material and that on a massive fine grained, dark amphibolite (see figure 3.3.B). Both the eclogite and the marble contain cracks that appear to be continuous either side of the quartzo - feldspathic material, both oriented to approximately 140°. In the eclogite these are filled by dark amphibole whilst in the marble they are of pale tremolite. These filled cracks do not occur in the quartzo - feldspathic material or in the amphibolite.

3.3 Loch Coire an Daimh

One hundred metres WSW of Loch Coire an Daimh (GR. 842216) is a low ridge of eclogite running NE - SW. The eclogite is intimately associated with variable amounts of quartzo - feldspathic rock, which generally lessens in abundance towards the SW. To the east of this ridge of eclogite there is a poorly exposed band of marble. To the west the land falls away steeply with no exposure until it flattens out at a second marble band. The eclogite at this locality thus lies to the west of the marble band seen beneath the eclogite at Lochan na Beinne Faide, described in section 3.2 above, and thus occupies a position along strike corresponding to that of the garnet - biotite - quartz - feldspar rock seen on Beinn Fhada, described above.

The eclogite is a fine grained pyroxene - rich rock containing small dark red garnets up to 2 mm across in a matrix of pale green pyroxene. The rock contains variable amounts of quartzo - feldspathic material, from thin discontinuous wisps of quartz up to 5 mm across and a few cm long, to wide patches and bands of streaky anastamosing garnet - quartz - feldspar enclosing small patches of pyroxene with or without garnet (plate 3.2.C). This streaky garnet - quartz - feldspar material contains garnet of similar appearance to that in the surrounding eclogite, although occasional garnets are larger and straddle the thinner quartz - feldspar layers entirely. In thick or coarse grained bands, small crystals of kyanite up to 2 mm long can be seen. Nearby, the weak foliation in the quartz - feldspar rich parts of the eclogite is oblique to the banding between quartz - feldspar bearing and quartz - feldspar free parts of the eclogite by about 15° (plate 3.2.D). As at Lochan na Beinn Faide, there are large patches of coarse grained, garnet - rich rock, up to 50 cm's across (plate 3.3.A).

All of this material is cut by cracks filled with dark green amphibole, most commonly oriented towards 140°, although often there are two distinct orientations, with a second set running sub-parallel to the weak foliation in the eclogites outlined by the quartz - feldspar streaks. These cracks are of variable intensity and of variable thickness, from a few mm to 5 cm wide. In the widest, a gradual change from eclogite to garnet - amphibolite to garnet - free amphibolite can be seen over a few cm towards the vein core, although garnets in the quartz - feldspar streaks often persist within otherwise garnet - free rocks (plate 3.3.B). Some of these cracks have a narrow yellow core of epidote and actinolite, other rare cracks have an outer rim of pale yellow epidote and actinolite between the dark amphibole and the eclogite.

Thin bands of foliated quartz commonly cut across the eclogite. These are up to 1 cm across and appear to pass along strike into the streaky quartz - feldspar rich parts of the eclogite described above. This foliated quartz has a different orientation to the streaky quartzo - feldspathic material and is often seen to cut the layering defined by the latter (plate 3.5.B). The foliated quartz is cut by the narrow yellow epidote - actinolite filled cracks, similar to the cores of dark - amphibole filled cracks. In places the quartz - feldspar rich parts of the eclogite form straight sided veins, occasionally with a strong lineation.

Although most of the eclogite along the crest of the ridge is fairly fresh, to the north and west alteration has occurred. To the north, alteration of the eclogite appears to have taken place without deformation. There is a gradual change from eclogite to garnet - amphibolite, in which garnets up to 2 mm across occur in a quartz - feldspar - dark green amphibole rock. This is cut by the amphibole - filled cracks outlined above, in the eclogite, but there are far fewer of them. A further change then occurs with the gradual replacement of garnet by pale yellow epidote. In this epidote - amphibolite there are a few rare amphibole veins (plate 3.3.C). To the west are sporadic outcrops of deformed, foliated epidote - amphibolite with or without streaks of quartzo - feldspar material, but usually with some foliated quartz bands. None of these deformed, foliated rocks are seen to be cut by the amphibole - filled cracks.

South of this outcrop, between it and the Glen More of Glenelg, the eclogite occurs as a continuous strip similar to that described above, with variable amounts of quartzo - feldspathic material and at various stages of retrogression. It is continuously bounded by two bands of marble, both of which have a large proportion of calc - silicate rock associated with them. The calc - silicate weathers to a characteristic rusty orange brown, occurring either as huge lumps, 5 to 10 m across, probably enclosed within the marble, or else as bands alongside the marble. Mapping of the eastern marble band shows that it is of variable thickness and that it branches a number of times. It is cut by a large number of cracks filled by white tremolite, that are often oriented towards 140°. Sometimes these filled cracks carry a good lineation. Eclogite from GR. 839209 is a garnet rich rock, consisting of about 70% garnet, 20% pyroxene and 10% quartz. It also contains large irregular patches of quartz - feldspar - kyanite, up to 1 cm across, as well as streaks of quartz, feldspar and kyanite. It is cut by dark amphibole filled cracks.

3.4 South coast of Loch Duich :- Hazel Brae and Fern Villa

The coast section north of Hazel Brae, past Fern Villa, contains a variety of rocks in widely differing states of deformation, ranging from intensely deformed amphibolite on the shore at Hazel Brae, to pods of eclogite in schistose material on the shore near to Fern Villa, to massive eclogite on the coast NW of Fern Villa. The eclogite bearing rocks occurring NW from Fern Villa are described first, followed by the more heavily deformed rocks outside Hazel Brae. Figure 3.4 is a sketch map of this coastal section.

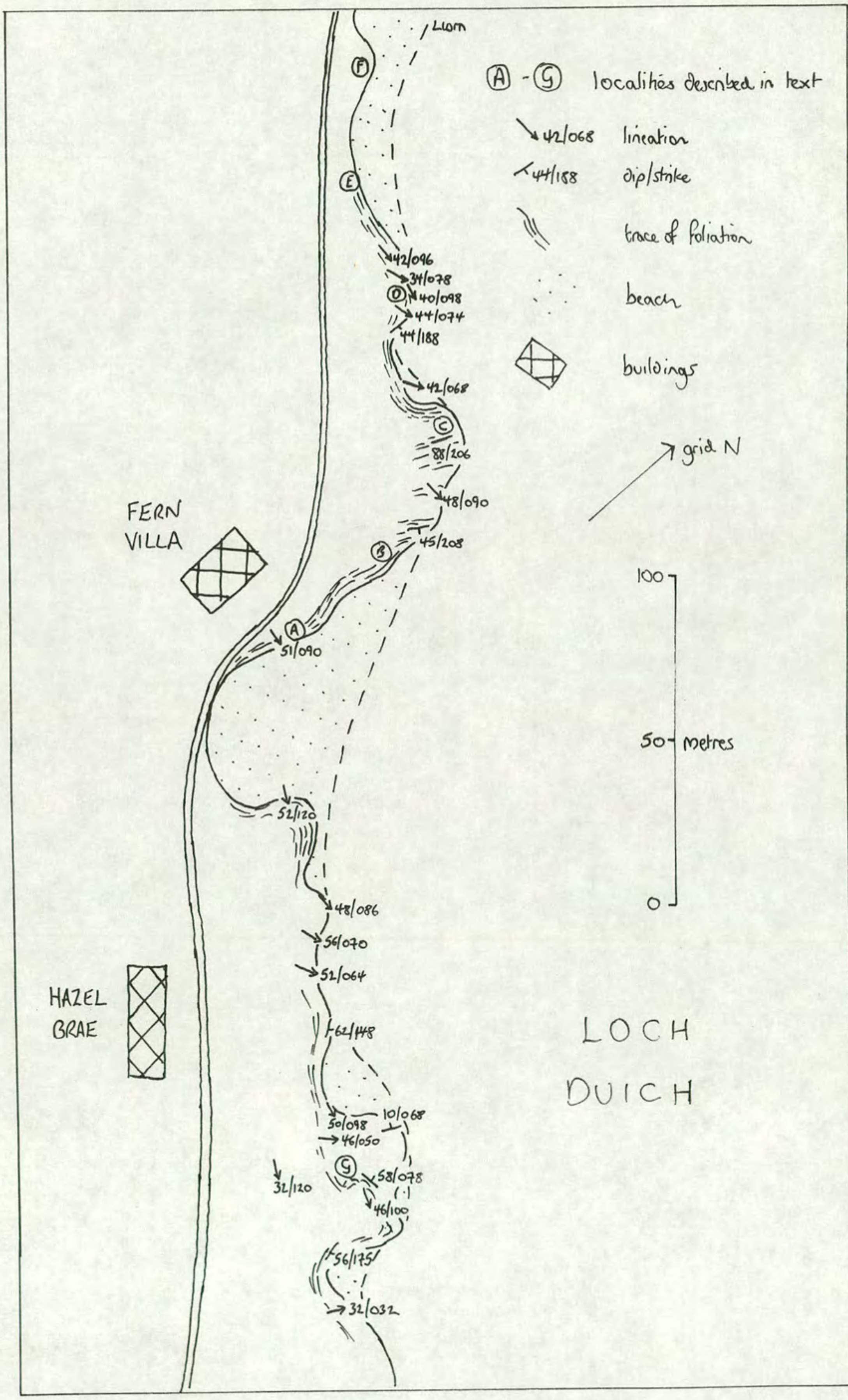
Along the coast from Fern Villa (location A) to location D (marked on figure 3.4) the outcrop consists of banded amphibole - rich and quartzo - feldspathic schists, interbanded on a cm scale, both bearing a strong lineation of variable orientation, all of which are gently folded. Around location A there are pods of massive amphibolite within this material, consisting of dark amphibole with or without quartzo - feldspathic patches.

At location B (figure 3.4) there is a pod of orthopyroxene - eclogite, consisting of aggregates up to 2 cm across of large bronze - coloured orthopyroxene crystals in a fine - grained, pale - green matrix. This pod is cut by two orientations of dark green amphibole filled cracks a few mm across (plate 3.6.A). It is also cut by narrow veins of quartz - feldspar rich material, which have a 2 mm thick rim of speckled, very fine grained amphibole. The pod is bounded to the SE by a large, virtually pure, biotite pod, itself bound by foliated quartz - feldspar rich material. To the NW the orthopyroxene - eclogite pod appears to grade out to both massive and sheared amphibolite, although the exposure is poor. At the NW end of the orthopyroxene - eclogite pod, the biotite pod is cut out by the foliated quartzo - feldspathic material, which here becomes much less deformed, being a gently folded coarse grained quartz - feldspar - amphibole rock.

At location C (figure 3.4) the general schistosity is oriented NE - SW and includes bands of garnet - biotite - quartz - feldspar schist and garnet - bearing mafic schists. The garnet - biotite - quartz - feldspar rock contains small red garnets up to 2 mm across in a matrix of biotite and quartz - feldspar. The mafic rock has garnets of similar appearance, in a dark fine grained matrix. Neither of these rock types contains dark amphibole - filled cracks or carries a lineation.

Pods of eclogite occur at location D (figure 3.4), similar to those described at Loch Coire an Daimh, in section 3.3 above (plate 3.4.A), with parallel sided streaks of quartz - feldspar, and dark green amphibole filled cracks. The quartz - feldspar streaks carry a lineation.

Figure 3.4 (following page) : Sketch map of the SW coast of Loch Duich from Hazel Brae (GR 887233) to north of Fern Villa (GR 885235)


Lùon
A - G localities described in text
42/068 lineation
44/188 dip/strike
trace of foliation
beach
buildings
grid N
100
50 metres
0
FERN VILLA
HAZEL BRAE
LOCH DUICH
F
E
42/096
34/078
D
40/098
44/074
44/188
42/068
C
88/206
48/090
45/208
B
A
51/090
52/120
48/086
56/070
52/064
62/148
50/098
10/068
46/050
G
58/078
32/120
46/100
56/175
32/032

From location E (figure 3.4) northwards there are many occurrences of eclogite with none of the schists seen along the rest of the section to the south. At location E there is massive eclogite, which is altered in patches to garnet - amphibolite. At location F (figure 3.4) there is a foliated eclogite in which the foliation is orientated vertically, and striking NE - SW. This is cut by horizontally lying, dark green amphibole - filled cracks, with narrow pale cores (plate 3.4.B). However, most of the eclogite in the vicinity of locality F consists of massive, coarse - grained eclogite with garnet and pyroxene occurring in roughly equal proportions, up to 3 mm across, and cut by a few dark green cracks. This eclogite often contains biotite and/or amphibole and some quartz. The biotite occurs in diffuse bands, with the crystals all similarly oriented, roughly parallel to the foliation outlined above. At one point this eclogite is layered, consisting of thin layers of coarse grained garnet - rich eclogite, quartz - garnet rich eclogite and pyroxene - rich eclogite. Generally the garnet - rich eclogite is rimmed by the quartz - garnet rich variety, which is itself rimmed by the pyroxene - rich variety (plate 3.4.C).

The outcrop between Hazel Brae and Fern Villa does not have any eclogite. It consists of banded amphibole rich and quartzo - feldspathic schists, similar to the section north of Fern Villa, containing pods of massive amphibolite, dark green fine - grained rock of amphibole with or without quartz and feldspar. To the south, these pods are rarer and the deformation is stronger. On the shore outside Hazel Brae, the pods consist of green amphibole only, often with large randomly oriented crystals up to 1 cm long growing in a finer matrix. These pods are described further in Chapter six. The schistose material at Hazel Brae is folded by at least two sets of folds. The first set are rare. They have axial planes parallel to the strong lineation seen throughout the coast section. These tend to be small tight folds, with hinges oriented east or SE. The second set of folds tend to be large open folds that fold the lineation. Outside Hazel Brae, at locality G (figure 3.4), is a large open fold with many associated parasitic minor folds that fold the schistosity and the lineation (plate 3.6.B).

3.5 Localities of other rock types.

3.5.1 Other Eclogite localities

Eclogites occur throughout the Eastern Lewisian, but appear to be most common between Loch Duich and the Glen More. Mylonitised eclogites are found at a number of localities, particularly north of Loch Duich, and SE of the Strathconon fault near

Arnisdale. Garnets up to 5 mm across occur within a fine grained, pale green matrix of pyroxene, amphibole and quartz. The rocks usually have a banded appearance with narrow, mm scale, white, quartz - rich and green, pyroxene - amphibole - rich rock. The mylonites are cut by veins filled with epidote.

Rare orthopyroxene eclogites occur within the Eastern Lewisian, other than that described above alongside Loch Duich. O'Hara (1960) and Mercy and O'Hara (1965) describe two other locations between Loch Duich and the Glen More. A further locality was found at GR. 853217, where orthopyroxene - bearing eclogite is invaded by quartzo - feldspathic veins. At a locality just south of the Glen Beag, GR. 829161, rare orthopyroxene was found in thin section.

3.5.2 Metasediments

Generally speaking, the rocks to the north of the Glen More are dominated by eclogitic assemblages and their retrogressed equivalents, described above. To the south of the Glen Beag metasedimentary rocks are apparently more common, although eclogites still occur and remain the best exposed rock type.

Along the Glen Beag the Eastern Lewisian is exposed due to folding along with the Moine (Ramsay, 1957). There are a number of exposures of marble along the valley and, towards the head of the valley, a large expanse of pelite. This is a garnet - kyanite - mica - quartz - feldspar rock, containing dark red garnets up to 5 mm across and needles of pale blue kyanite up to 4 mm long and 2 mm across, both set in a matrix of fine grained, foliated, folded mica - quartz - feldspar which generally carries a good lineation.

Between the Glen More and the Glen Beag there are many occurrences of eulysite. This rock is similar in appearance to the eclogite. It consists of small dark red garnets up to 2 mm across in a matrix of fairly fine grained dark amphibole, with or without quartz - feldspar. Alteration is patchy and produces a dark, fine grained garnet free equivalent of the same rock.

Approximately 1 km north of the outcrop described at Lochan na Beinn Faide, close to the easternmost of the two marble bands, is an extremely garnet rich rock. Pale red garnet comprises at least 80% of the rock as coarse, often equant crystals up to 2 cm across, occurring with quartzo - feldspathic material and rare black biotite.

3.5.3 Other basic rock types

Rare basic rocks occur which, in thin section, described in chapter six, do not show obvious relicts of high grade metamorphism. Although they generally form massive nodules within schistose rocks, no cross - cutting relationships have been found. The rocks described in this thesis are plagioclase - free amphibolites, consisting primarily of amphibole, epidote and sphene with or without quartz, but (in thin section) there is no sign of rutile, or of sieved amphibole after pyroxene. Plagioclase - bearing varieties are described by May *et al.* (1993). The quartz - free varieties of these rocks are obvious and occur as massive, rounded, dark green or black nodules within banded amphibolites, common at Hazel Brae, described above. Quartz - bearing samples are probably different to retrogressed eclogites when seen in thin section, but virtually indistinguishable in the field. At GR. 899239, in a road cutting on the new road alongside Loch Duich (the A 87), a layer of massive and fine - grained, quartz - bearing amphibolite is smeared out and boudinaged within the surrounding banded amphibolite (plate 3.6.C). May *et al.* (1993) also mention the occurrence of anomalous plagioclase - bearing amphibolites north of Loch Duich.

3.5.4 Ultrabasic rocks

Ultrabasic rocks occur throughout the Eastern Lewisian as pods within fine grained schistose banded - amphibolite. Generally the pods consist of soapy white talc and pale green serpentinite, although some pods consist of coarse grained very dark green amphibole, up to 2 cm across. North of Loch Duich, at GR 892247, in a cutting on the old road along Loch Duich, a pod of websterite occurs, mentioned by Sanders (1972). This consists of coarse - grained, bright - green clinopyroxene and bronze - coloured orthopyroxene, both up to 3 cm across, with small flakes of golden phengite scattered throughout. The pod has a thin rim of black biotite, a few mm thick, and sits in fine grained schistose amphibolite, although occasional thicker bands of massive amphibolite alongside the pod are garnet bearing.

3.6 Interpretation of field observations

The oldest basic rocks recognisable in the Eastern Lewisian are the fresh eclogites. Quartz and orthopyroxene - bearing eclogite are fairly restricted in occurrence, but Sanders (1972) suggests that the occurrence of either quartz or orthopyroxene within eclogites is due to changes in bulk rock composition and that all the eclogites represent a single suite of rocks.

The occurrence of black amphibole and/or biotite, with or without quartz and feldspar seems to be restricted to bimineralic eclogites. The association of black amphibole and garnet at Lochan na Beinne Faide, with or without biotite and quartzo - feldspathic material, probably indicates the partial alteration of the eclogite on hydration at high pressure and temperature, with the anhydrous eclogite mineralogy being recrystallised to form a garnet - pyroxene - amphibole - (biotite) - (quartz) - (feldspar) rock, perhaps similar to the garnet - pyroxene - biotite rock described at locality F, at Fern Villa.

Quartz - feldspar - (kyanite) - (garnet) streaks occur throughout the Eastern Lewisian. They are identifiable not only within the eclogites, but also in some of the marble nodules at Lochan na Beinne Faide and in pelitic garnet - biotite - quartz - feldspar rocks. Sanders (1988) suggests that the quartz - feldspar - (kyanite) material represents the sites of former feldspar within the basic rocks. However, the occurrence of similar streaks within both the eclogites and the metasediments suggests that this material could represent the intrusion of acid igneous material into the eclogites and surrounding rocks during or after high - grade metamorphism, perhaps similar to the common intrusion of tonalitic sheets into the Scourian after initial high grade metamorphism, prior to later high grade metamorphism and deformation (Rollinson, 1994).

These changes represent early alteration of the eclogite. They all occur prior to a phase of deformation that affected the eclogite, producing a weak foliation within the eclogites seen as oriented quartz wisps in quartz - eclogite, and elongate streaks of quartz - feldspar - (kyanite) - (garnet).

All the eclogitic rocks are cut by dark green amphibole - filled cracks, many of which have a core of pale yellow epidote - actinolite. The dark amphibole appears to represent the alteration of the host rock either side of a crack, whilst the yellow material appears to be filling up cracks in the rock, with little interaction with the wall rock. The absence of epidote - actinolite from the cores of many of these cracks, and the rare occurrence of epidote - actinolite without alteration at the rims, implies that the occurrence and filling of cracks has occurred twice. Cracks similar to those filled by dark amphibole also occur with different mineralogies in other rock types, particularly in the marbles.

The general retrogression of the eclogites occurred after the initial deformation of the rocks because at Loch Coire an Daimh already deformed quartz - eclogites with wisps of quartz outlining a weak foliation pass into garnet - amphibolite and then epidote - amphibolite. This general retrogression cannot have occurred before the formation of dark hornblende - filled cracks without epidote cores because only epidote - actinolite - filled cracks are seen in the retrogressed material. It is probable that alteration to produce hornblende - bearing veins within the eclogite is synchronous with widespread general retrogression to produce schistose amphibolite and that the presence of differing quantities water has influenced the amount and type of deformation and retrogression. Where the rocks have remained dry the eclogite mineralogy has remained stable and the rocks have suffered brittle deformation with fluid restricted to cracks across the rock. Where wet the rocks have suffered deformation in a more ductile manner and have been widely retrogressed to garnet amphibolites. The formation of epidote - actinolite - filled cracks occurred after this general deformation and is seen in many of the rocks of Glenelg, both amphibolites and eclogites. However, they are not seen in garnet - free, epidote - bearing amphibolites and it is reasonable to assume that during later deformation events there was both brittle and ductile deformation related to water content in a similar manner to that above. Brittle deformation occurred in the eclogites and some of the garnet - amphibolites, with epidote and actinolite filling cracks produced by this deformation, whilst in rocks that became wet during deformation further retrogression and ductile deformation occurred to produce epidote - amphibolites.

In chapter two the characteristics of the main deformation events were outlined and, by correlation with previous work, it is probable that the main deformation represented by the schistose rocks along the coast sections is of D_2 age, because it bounds pods bearing two earlier phases of deformation, thought to be D_0 and D_1, the former a weak foliation seen in some wispy quartz - bearing eclogites, thought to occur prior to Moine deposition, the latter a strong deformation producing strongly schistose quartz bands within the eclogite both inland and on the coast. The schistosity bounding the pods cuts cracks filled with dark amphibole, which are therefore probably pre - or syn - D_2, whilst those filled by epidote - actinolite are probably pre - or syn - D_3.

Rare massive pods of basic, but possibly non - eclogitic, rock occur within sheared amphibolite throughout the Eastern Lewisian. It is likely that some of these represent undeformed, but heavily retrogressed eclogite, particularly those alongside Loch Duich at Hazel Brae, but others appear to be amphibole - quartz - epidote bearing rocks without any of the relict eclogite facies textures. Rocks with such a mineralogy occurring as nodules and occasional bands within schistose rocks would be expected to preserve some relict textures if they had previously been affected by eclogite facies metamorphism. The boudinaged rock described on the NE coast of Loch Duich in particular possibly cuts across a previously deformed rock and may represent some basic intrusion into it, discussed in chapter six. Other plagioclase - quartz - free nodules may not be directly related to the eclogites, but could either be altered websterites or other, more ultrabasic, intrusions. The possibility of there being basic rocks within the Eastern Lewisian that were not metamorphosed at high grades was mentioned by Barber (1962) and May *et al.* (1993) and is further discussed in chapter six. Much of the interpretation of the history of the area hinges on whether these rocks are indeed altered eclogites and websterites or else metamorphosed dykes intruded after eclogite facies metamorphism.

The occurrence of folded nodules within the marbles, and of rare sheared veins across it, both of which carry a lineation, implies either that the marble was a rigid, coherent body during the late deformation and that nodules of meta - igneous rocks must have entered the marble early in the history of the rocks, or that the marble was a soft body that reacted fluidly with basic rocks squeezed into it during deformation. The presence of strongly foliated quartz - feldspar - kyanite material at the edge of one marble outcrop implies that the marble acted in a rigid manner during late deformation. Also, Sutton and Watson (1958) mapped a mylonite band along the entire eastern edge of one of the bands, indicating that it probably reacted to later deformation in a rigid manner.

The pelites of the Glen Beag show part of the history shown by the retrogressed eclogite along the shore of Loch Duich. They show a foliation, outlined by orientated flakes of mica, which has been folded by tight minor folds bearing a lineation, and with a weak axial planar cleavage. These presumably correspond to the regional D_1 and D_2 events of Ramsay (1963).

Of the other rock types, little can be said of their histories from field evidence, due to the poor exposure.

From this summary of the history of the Eastern Lewisian, five important questions are raised, and considered in the following chapters.

1) Some basic nodules within retrogressed eclogites, now amphibolite facies schists, may represent dykes intruded into the Eastern Lewisian after eclogite facies metamorphism, as suggested by May *et al.* (1993), although no actual cross - cutting relationships are found. The implications of this are that the Eastern Lewisian may have had a similar history to the Lewisian of the foreland, in which case the eclogites could be Scourian in age.

2) The quartzo - feldspathic streaks within many of the eclogites may have been intruded into the eclogites after initial high - pressure metamorphism, rather than solely representing sites of original plagioclase as suggested by Sanders (e.g. 1972), because they occur in both metasediments and eclogites.

3) The occurrence of quartz eclogite may or may not be related to the occurrence of quartz - feldspar - kyanite streaks, because at Loch Coire an Daimh the wisps of quartz comprising the quartz - eclogite appear to be a transition phase from bimineralic eclogite to eclogite containing streaks of quartz - feldspar - kyanite.

4) The occurrence of quartz - feldspar - kyanite streaks is common in many eclogites, but is not seen at Lochan na Beinn Faide. Here amphibole and biotite (with or without feldspar and quartz) occur with garnet and pyroxene. It may be that the two phenomena are related. These two questions can only be answered once the petrology and chemistry of the eclogites has been discussed.

5) Some of the eclogites have suffered cataclasis, ductile deformation and brittle cracking during their deformation and retrogression. It is not immediately clear how each of these styles is related to each other, a problem which is not properly addressed by this thesis due to the lack of detailed fieldwork required.

Plate 3.1.

A) Bimineralic eclogite from near Lochan na Beinne Faide, GR 862235. Red garnet and pale green clinopyroxene.

B) Part of coarse garnet within bimineralic eclogite near to Lochan na Beinne Faide, GR 862235 (Yellow is lichen).

C) Red garnet and pale green clinopyroxene with black amphibole partly surrounding and replacing garnet in eclogite from near to Lochan na Beinne Faide, GR 862235.

D) Part of coarse garnet with alteration along cracks to black amphibole and white plagioclase, near to Lochan na Beinne Faide, GR 862235 (field of view : 12 cm).

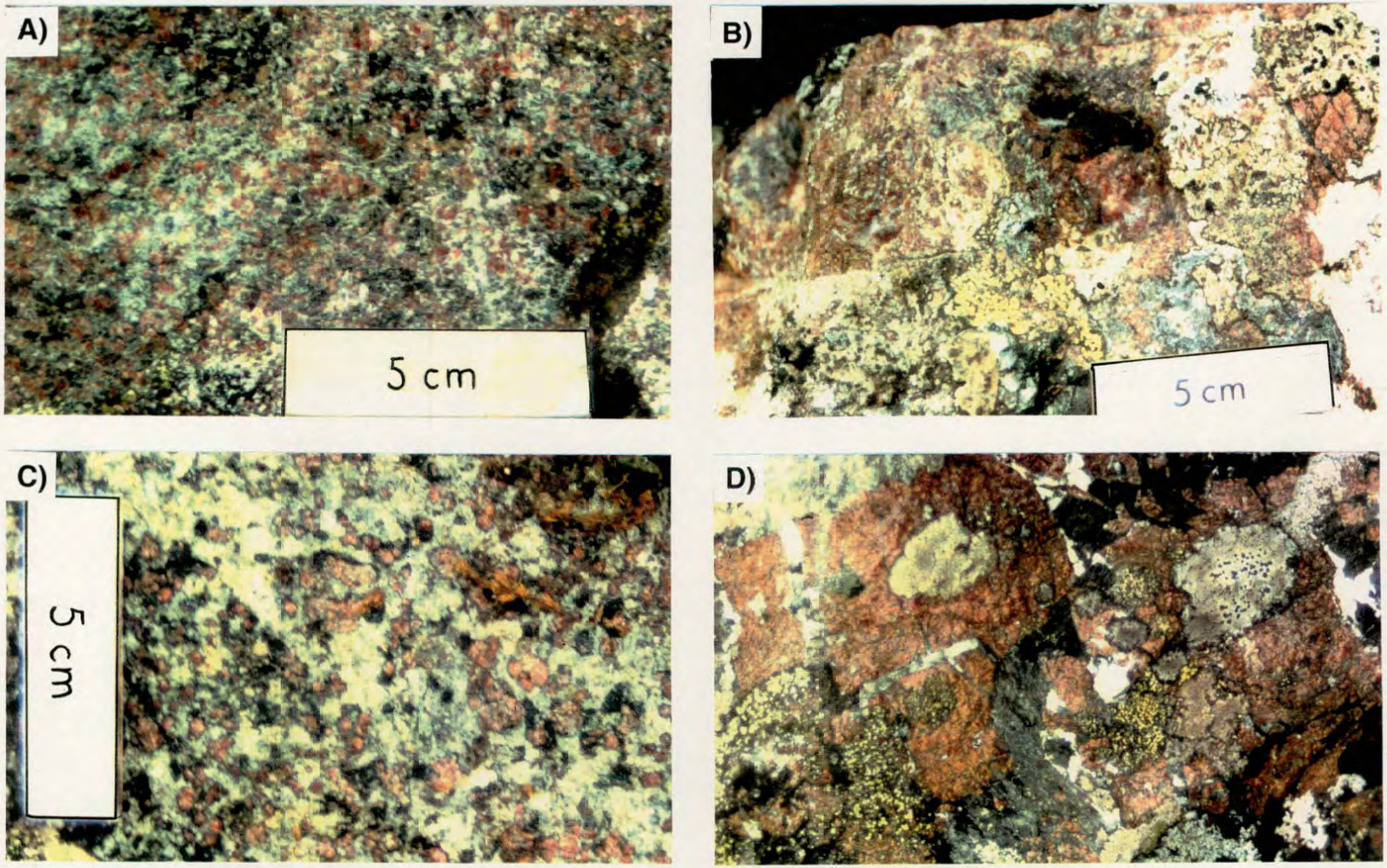

A)
5 cm
B)
5 cm
C)
5 cm
D)

Plate 3.2.

A) Part of cliff of nodular marble near to Lochan na Beinne Faide. Large rounded nodules of white diopside and dark elongate ones of metabasic rock. Looking N at GR 862235.

B) Layered marble cut by tremolite filled veins, on a gently sloping surface facing N at GR 860234.

C) Quartz - eclogite near to Loch Coire an Daimh, GR 843216. Scale is oriented approx. E-W. Eclogite with variable amounts of quartz, cut by amphibole filled veins.

D) Eclogite and quartz - eclogite near to Loch Coire an Daimh, GR 843216. Scale is oriented approx. NE-SW. Foliation in the quartz - eclogite is oblique to the layering between the two.

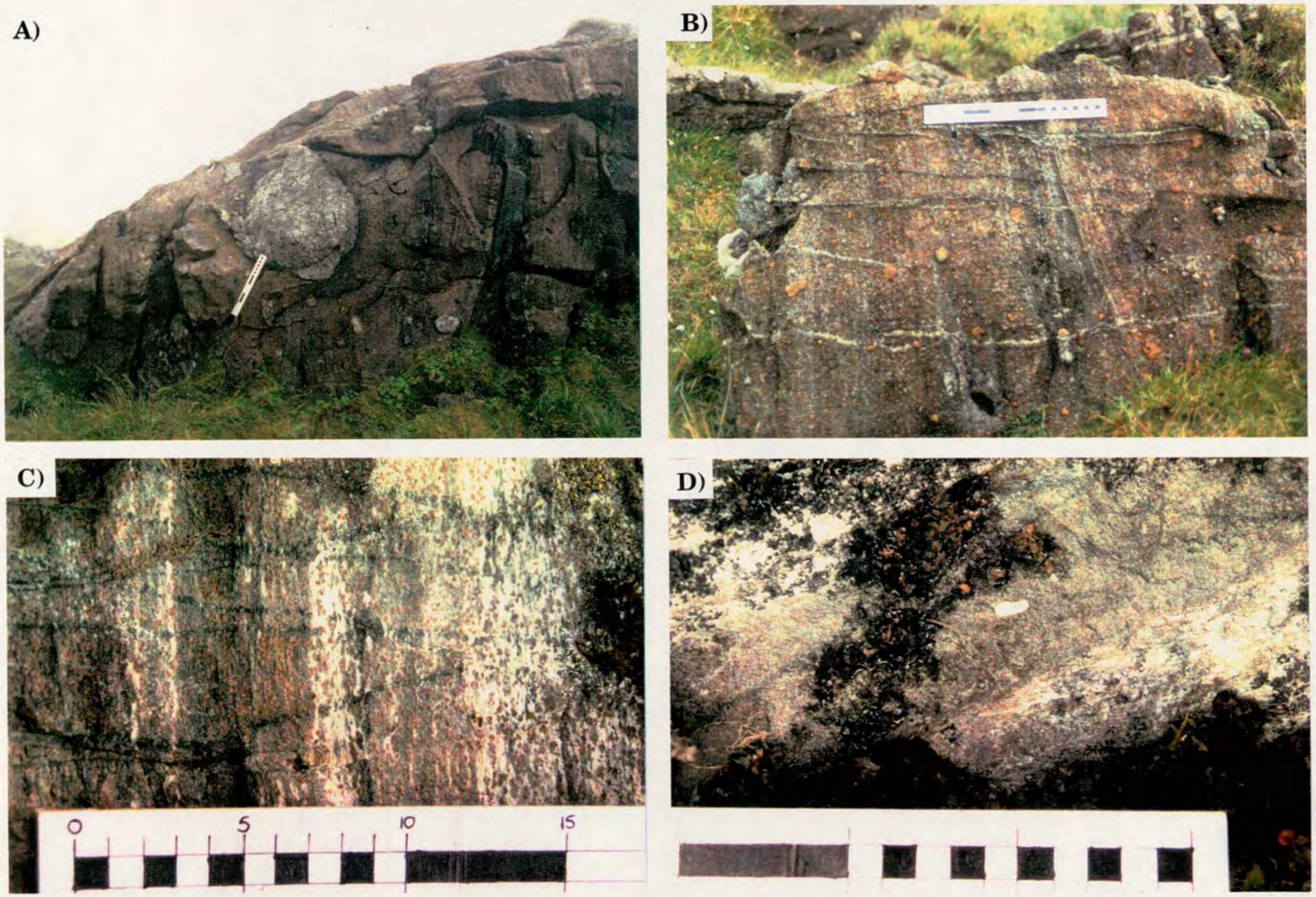

A)
B)
C)
0
5
10
15
D)

Plate 3.3.

A) Garnetiferous layer within quartz - eclogite near to Loch Coire an Daimh, GR 842216, cut by amphibole - filled veins. Looking N.

B) Quartz - eclogite cut by amphibole - filled veins near to Loch Coire an Daimh, GR 842216, scale oriented approx. N-S. These veins have pale cores of epidote and actinolite and dark rims of hornblende. The two do not always occur together.

C) Quartz - eclogite (left) passes to amphibolite (centre) and epidote - amphibolite (right). Amphibole - filled veins fade out into the latter. Near to Loch Coire an Daimh, GR 842216. Scale is oriented approx. E-W.

D) Eclogite pod (centre) defined by foliated quartzo - feldspathic rock (left and right) at Sgurr an t - Sabhail, GR 880248. Hammer shaft is oriented approx. NE-SW (Locality is no longer exposed due to road building).

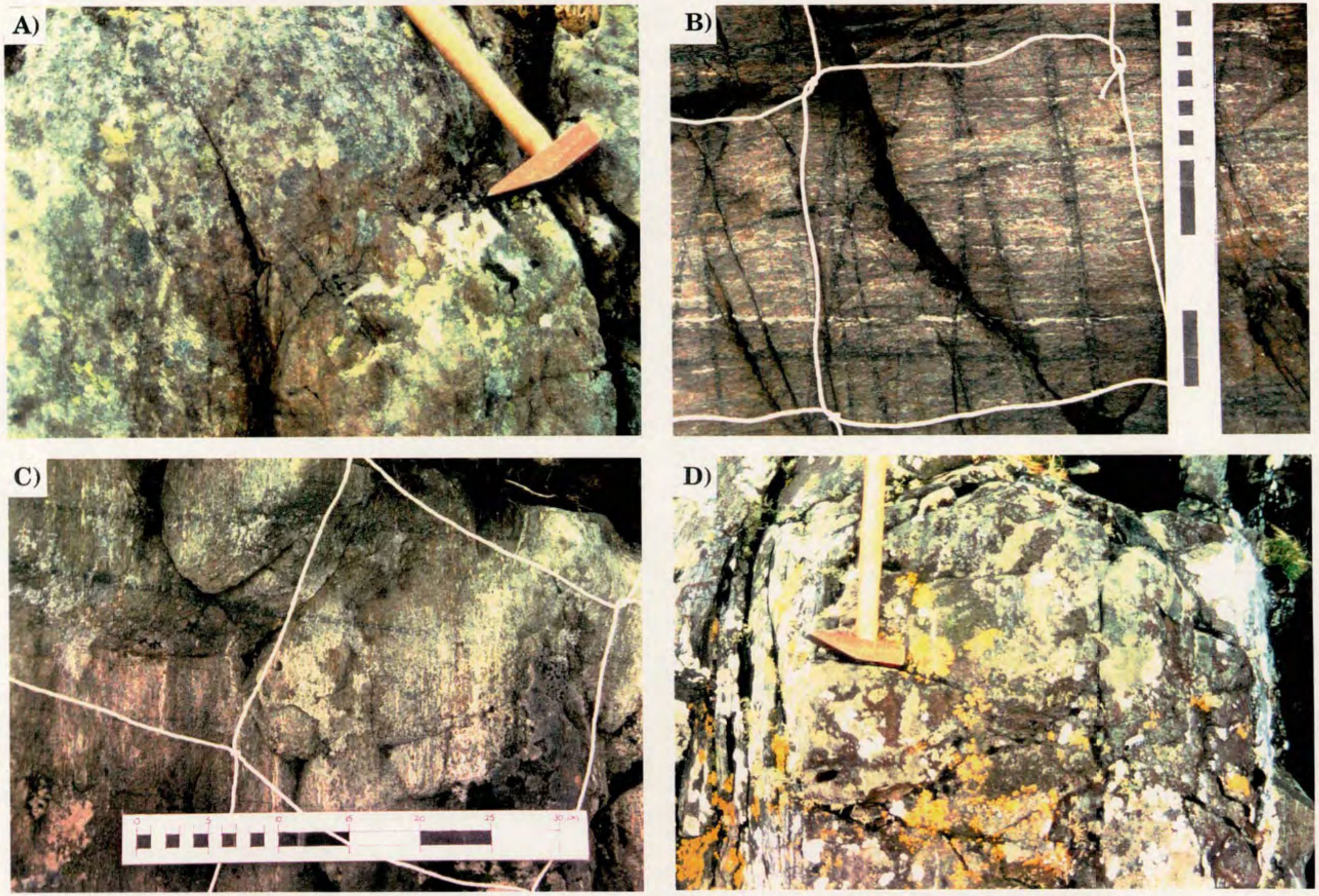

A)
B)
C)
D)

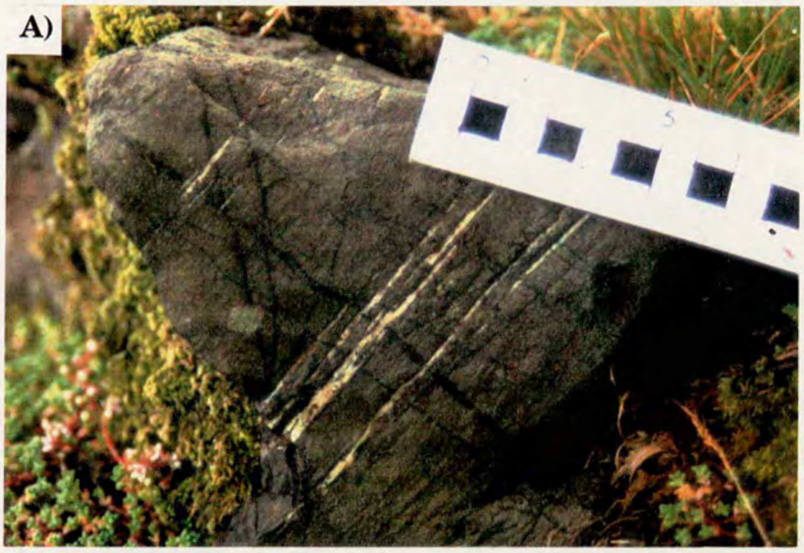
Plate 3.4.

A) Quartz - eclogite cut by amphibole filled veins, on the south coast of Loch Duich north of Fern Villa, GR 886234, looking SE.

B) Quartz - eclogite cut by composite veins with pale epidote and actinolite cores and dark hornblendic rims on the south coast of Loch Duich north of Fern Villa, GR 885235. Scale is oriented NE-SW.

C) Eclogite with garnet rich, garnet - quartz rich and pyroxene rich layers on the south coast of Loch Duich north of Fern Villa, GR 885235, looking NW.

A)



B)

C)

Plate 3.5.

A) Detail of metabasic nodule within marble. Nodule has conspicuous red garnets up to 5 mm across, a strong fabric emphasised by quartz - feldspar rich and mafic rich layers. The nodule is folded into the marble (Scale is 12 cm across). Near to Lochan na Beinne Faide, GR 862235, looking N.

B) Patches of quartz - rich eclogite with a weak foliation and quartz - poor eclogite without, both cut by strongly foliated quartzo - feldspathic material. Near to Loch Coire an Daimh, GR 842216, looking NE.

C) Pod of eclogite within foliated amphibolite at Sgurr an t - Sabhail, south coast of Loch Duich, GR 880248 looking SW (locality is no longer exposed due to road building).

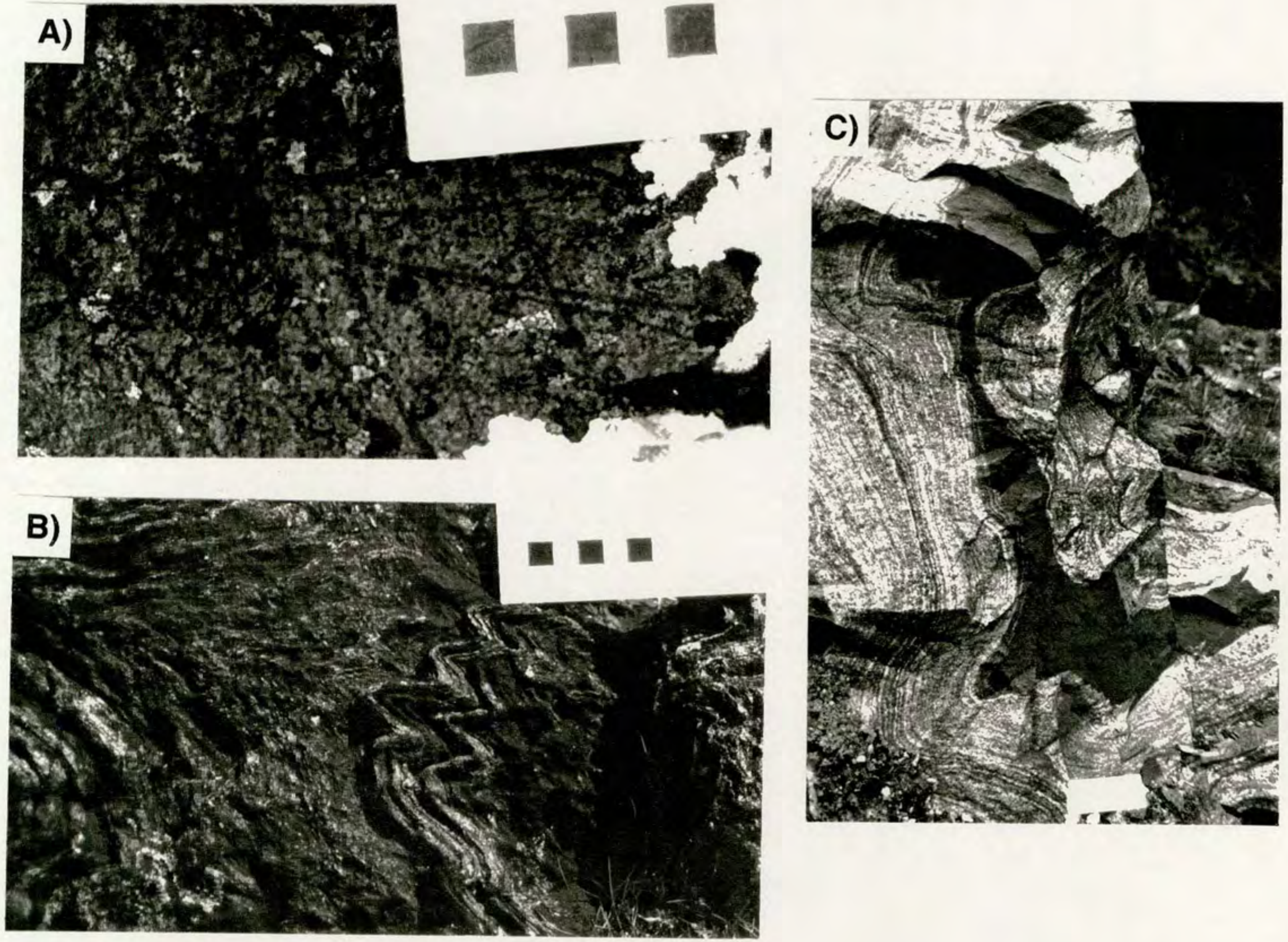

A)
B)
0
5
10
C)

Plate 3.6.

A) Orthopyroxene eclogite (SN. 511) with large golden orthopyroxene crystals (e.g. centre left). Cut by amphibole - filled veins. On the south shore of Loch Duich, north of Fern Villa, GR 887233.

B) Tight D_3 folds in amphibole - rich rock, on the south shore of Loch Duich at Hazel Brae, GR 888232, looking NE.

C) Stretched and boudinaged amphibole - rich layer within deformed schistose amphibolite, on the north shore of Loch Duich in a road cutting, GR 896240.


A)
B)
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Chapter Four

Petrography of the Eastern Lewisian rocks and their retrogressed equivilants

CHAPTER 4

Petrography of the Eastern Lewisian Eclogites and their retrogressed equivalents

4.1 Introduction

In chapter three the field relationships of the Eastern Lewisian rocks were described, concentrating on the basic rock types. Four types of eclogite were identified. The most common type is a coarse grained bimineralic garnet - clinopyroxene rock. Two other types, quartz - bearing and orthopyroxene - bearing, are more rare. All these eclogite types sometimes contain streaks of quartz - feldspar - kyanite (QFK), possibly related to patches of dark amphibole with or without biotite and plagioclase seen in some QFK free bimineralic eclogites. A fourth type, biotite - rich eclogite, occurs at one locality on the coast of Loch Duich. The petrography of the bimineralic eclogites was described by Alderman (1935) and Sanders (1972) and the quartz - feldspar - kyanite streaks in eclogite briefly by Sanders (1988), but they are both further described here to provide a background to descriptions of the later history of the rocks. Mercy and O'Hara (1968) and Sanders (1972) described orthopyroxene - bearing eclogites, but in this chapter rocks from three further localities are described, each of which is slightly different to the others and to those previously described. The interpretation of the history of the Eastern Lewisian rocks rests largely on a small number of key samples in which many of the events that have affected the eclogites are preserved.

Five deformation events were outlined in chapter three and were tied into the structural history discussed in chapter two after previous workers. The first event, D_0, affected basic rocks after the intrusion of QFK streaks and occurred under dry, high pressure - temperature conditions, estimated by Sanders (1988) as being 17 Kb, 750°C. The later events D_1 - D_4 occurred after the deposition of Moine rocks and occurred under generally hydrous conditions at lower grades of metamorphism, in which amphibole and plagioclase were stable instead of garnet and pyroxene.

4.2 Eclogitic rocks

4.2.1 Bimineralic eclogite

The best examples of fresh bimineralic eclogite are found near to Lochan na Beinne Faide, described in section 3.2 above. They consist of approximately 60% pyroxene and 40% garnet with minor amounts of rutile and rare quartz. Garnet occurs as anhedral pale pink crystals, generally up to 3 mm across, but sometimes up to 6 mm across. Pyroxene occurs as large anhedral pale green crystals of similar size, occasionally with tiny sphene inclusions in the cores. The pyroxene is often slightly elongate, defining a weak fabric. Both garnet and pyroxene contain inclusions of each other and also of rutile crystals up to 0.5 mm across, although rutile tends to occur at garnet and pyroxene grain boundaries. Quartz is extremely rare but when it does occur it forms small crystals between garnets and pyroxenes (SN. E1 - E11) (plate 4.1.A).

Occasionally hornblende and, more rarely, biotite, occur up to 1 mm across. The hornblende is pleochroic from dark brown to pale brown to olive green. The biotite is pleochroic from almost colourless to fox brown. Both minerals tend to occur between grains of garnet and pyroxene, often growing with equant grain boundaries to the garnet (SN. E5). In rare samples large amounts of hornblende, biotite and plagioclase occur (SN. E2) apparently in equilibrium with garnet and clinopyroxene. Generally the hornblende occurs as anhedral crystals up to 2 mm across, often with inclusions of biotite, plagioclase and more rarely, clinopyroxene and rutile. It has a pleochroic scheme similar to that above. Coarse grained symplectites are common in these samples, either of plagioclase - hornblende (plate 4.6.C) or of plagioclase - biotite (plate 4.6.D), in both cases with some garnet and clinopyroxene present. The crystals comprising the symplectite are up to 1 mm across. The plagioclase - hornblende symplectites often occur between large hornblende grains and plagioclase (SN. E9).

In some bimineralic eclogite, such as SN. 96, with QFK streaks, both garnet and clinopyroxene only occur as interlocking polygonal crystals, both up to 0.5 cm across.

At some stage growth of extremely coarse garnet up to 20 cm across occurred, as described in section 3.2 above at Lochan na Beinne Faide. These garnets occur as large single crystals that are either virtually inclusion free or else, more rarely, contain up to 20 % inclusions of subhedral pyroxene, normally up to 3 mm across, but sometimes up to 2 cm across. Some of these pyroxenes themselves have inclusions of garnet up to 0.5 mm across. Both types of coarse garnet within the eclogite are extensively cracked (SN. C1 - C5) (plate 4.1.B), with cracks filled by green amphibole.

4.2.2 Quartz - rich eclogites

The amount of quartz present in the eclogite is extremely variable. It sometimes occurs in minor amounts in the bimineralic eclogite, but otherwise occurs with garnet and clinopyroxene in two distinct occurrences, the first as numerous tiny inclusions within garnet, the second as part of garnet - clinopyroxene - quartz rocks containing up to 15 % or more quartz throughout the rock.

The former type consist of elongate anhedral pyroxene up to 1 mm across, often with tiny quartz grains occurring between them, and of subhedral garnets riddled with quartz inclusions less than 0.05 mm across which comprise up to 50 % of the garnet and which often partly outline an aggregate of roughly polygonal quartz - free garnets (plate 4.1.C, 4.5.A). In SN. 353, from Loch Coire an Daimh, there are patches a few mm across consisting of anhedral garnet and pyroxene which preserve similar textures to those described above, in section 4.2.1, which pass into the quartz - rich eclogite. This change from bimineralic eclogite to quartz - rich eclogite is accompanied by a general reduction in grain size, by a change from anhedral to polygonal crystals, and by the imposition of a crude layering into garnet - quartz aggregate rich layers and pyroxene - quartz layers. The garnet - quartz aggregate layers have variable amounts of quartz and occasionally garnet - rich aggregate passes into layers of mainly quartz with many small equant garnets up to 0.2 mm across and tiny rutile crystals (plate 4.5.B).

The latter type of quartz - eclogite are generally garnet - rich eclogites. SN. 83, from north of the Glen More of Glenelg (GR. 839209), consists of about 50% garnet, 15% pyroxene, 15% quartz and 20% irregular patches of quartz, feldspar, kyanite, biotite, garnet, rutile and sphene. Many of the garnets in the rock are large anhedral garnets, 2 - 3 mm across, with pale pink cores and colourless rims. Pyroxene and quartz are more fine grained than the garnet (plate 4.3.B). Many of the garnets have lines of inclusions of tiny sphene and quartz crystals, less than 0.01 mm across that outline subhedral cores prior to occurrence of anhedral overgrowths (plate 4.7.B). The rest of the garnets are small polygonal crystals up to 0.15 mm across, often clustered together with quartz between them. The pyroxene occurs as pale green elongate crystals and the quartz as elongate aggregates, between them they define a weak fabric. Sphene is far more common than rutile, occurring as rounded crystals throughout the rock that are slightly pleochroic from pink to colourless. Rutile tends to be restricted to inclusions in garnet and pyroxene and to the QFK patches. These QFK patches are elongate, but irregular in shape. They are made up mostly of large blades of kyanite, up to 1.5 mm long, and anhedral feldspar and quartz (plate 4.7.C). All three minerals are strained. Small, polygonal garnets occur, as do small patches of biotite - quartz symplectite. Rutile, sphene and ilmenite all occur along with iron oxide and sulphide. Other similar samples occur with distinct QFK streaks that either blend into the quartz - eclogite (SN. 350b) or else which are cut by deformed streaks of QFK (SN. 347).

Brown hornblende and biotite often occur with garnet - quartz aggregates. The hornblende is pleochroic from light brown to pale olive green to a pale yellowish brown. It tends to occur in distinct bands of hornblende - biotite - garnet aggregate, generally growing between garnet and pyroxene occurring at the edge of the band. The biotite is pleochroic from almost colourless to fox brown. It occurs in bands, but also sometimes occurs in smaller amounts throughout the rock, generally all oriented in a similar direction, parallel to the slight elongation of the pyroxene. Biotite also occurs as symplectites of biotite - quartz and at the rims of garnet - quartz aggregates. Garnet in the hornblende - biotite - garnet bands is anhedral and riddled with inclusions of quartz, biotite, hornblende and sphene.

4.2.3 Orthopyroxene - bearing eclogites

The field occurrences of orthopyroxene - bearing eclogites were described in sections 3.5 and 3.6. One sample, SN. 511, from the south coast of Loch Duich outside Fern Villa (GR 887233), described in section 3.5, is a bimineralic orthopyroxene - clinopyroxene rock, and as such is not an eclogite *senso stricto*. However, it is considered to be different to websterite, described in chapter six below, due to the occurrence of secondary garnet. The rock consists of approximately 70% clinopyroxene and 30% orthopyroxene, both of which occur as large, colourless, anhedral crystals up to 2 mm across. The orthopyroxene has a slightly higher relief and is always at least slightly altered to talc and iron oxide. Both the pyroxenes contain lamellae of garnet, whilst the clinopyroxene also contains many small inclusions of sphene and rutile, less than 0.05 mm across, and is also often surrounded by a semi - continuous chain of garnet up to 0.1 mm across. The garnet lamellae in orthopyroxene are fairly wide, up to 0.1 mm across, unevenly spaced and distributed, and cut across the entire crystal (plate 4.5.C). The lamellae in the clinopyroxene are narrow, parallel and usually evenly spaced, occurring either parallel to the sphene inclusions or else at 45° to them (plate 4.5.D). In places SN.

511 shows alteration similar to that described above in quartz - eclogite, with aggregates of garnet up to 0.15 mm across that contain tiny inclusions of quartz and also sphene and opaques, the last of which give the aggregates a dusty appearance. Polygonal clinopyroxene up to 0.2 mm across is common, often replacing coarse anhedral pyroxene. It occurs either with the garnet aggregate, or else with quartz, biotite, rutile and polygonal, inclusion free garnet (plate 4.6.A).

SN. 223 from north of the Glen More (GR 854215), is a two - pyroxene eclogite, although much of the rock has been invaded by QFK streaks, described in section 4.2.5 below. The mafic portion of the rock is made up mostly of equal proportions of garnet and clinopyroxene, with only about 10% orthopyroxene. The garnet and clinopyroxene both occur as large, colourless, anhedral crystals up to 3 mm across, whilst the orthopyroxene crystals are much smaller, up to 0.5 mm across (plate 4.1.D). The garnet tends to be inclusion free, but rare patches occur whereby the garnets have up to 50% large clinopyroxene inclusions. In places aggregates of garnet and quartz occur, often at the grain boundary between two large anhedral garnets (plate 4.2.A). These garnet - quartz aggregates pass laterally into QFK streaks. Large anhedral clinopyroxenes are rare. Those that do occur have many tiny sphene inclusions in their cores and are zoned from pale green in the centre to colourless at the rims, especially where they occur at the rims of QFK streaks. In general the large clinopyroxenes are pseudomorphed by smaller interlocking polygonal clinopyroxene up to 0.25 mm across with or without small subhedral garnet, quartz, biotite and rutile.

A third type of orthopyroxene eclogite, SN. 337, occurs south of the Glen Beag (GR 829161). It is a quartz - free rock, consisting of approximately 45% garnet, 35% clinopyroxene and 20% orthopyroxene, although the occurrence of orthopyroxene seems to be extremely localised. Seven samples have been collected from this exposure (SN.'s 217, 218 and 337 - 341) yet only one, SN. 337, contains orthopyroxene. The other six show no evidence of ever having contained orthopyroxene, and appear to have been bimineralic eclogite prior to the intrusion of QFK streaks. The garnet in SN. 337 occurs as large, pale pink, inclusion free, anhedral crystals, often greater than 2 mm across. The clinopyroxene tends to be slightly finer grained and occurs as inclusion free, pale green, strained, anhedral crystals. The orthopyroxene occurs as aggregates of small, strained crystals up to 0.15 mm across, with minor alteration at the grain boundaries to produce very fine grained talc and iron oxide (plate 4.2.B). Secondary green amphibole is ubiquitous throughout the rocks from this outcrop.

4.2.4 Quartz - feldspar - kyanite streaks

Quartz - feldspar - kyanite (QFK) streaks occur in many of the eclogites in Glenelg. The features of these streaks are best seen in the field at two localities, one south of the Glen Beag at GR 829161, the other from near to Loch Coire an Daimh, GR 842216, described in section 3.3 above. Sanders (1988) described and interpreted some of the textures seen within the QFK streaks. The streaks were interpreted as being sites of original plagioclase within the rock in which the plagioclase had broken down during high - pressure metamorphism. Garnet is concentrated at the rims of (some) QFK streaks. Sanders (1988) reports kyanite inclusions in garnet, but these are rare and have been recorded in only one sample, SN. 347.

The first locality, south of the Glen Beag, is that of SN.'s 217, 218, 337 - 341, of which SN. 337 is an orthopyroxene - bearing eclogite, described in section 4.2.3 above. There are both deformed and undeformed QFK streaks at this locality. SN. 218, contains large irregular patches of QFK occur up to 10 cm across, containing both garnet, up to 1 mm across, and pyroxene up to 0.25 mm across (plate 4.2.C). Garnet within the QFK streaks and at their margins tends to be subhedral. Kyanite up to 0.2 mm long is weakly orientated defining a fabric that often wraps around the large garnets. Both quartz and feldspar are either strained or have recrystallised to small interlocking polygonal crystals up to 0.3 mm across. In SN. 217 the QFK streaks are parallel sided. Blades of Kyanite are orientated along the length of the streaks. Garnets occurring within the streaks are subhedral. Very few coarse crystals of quartz and feldspar occur, most of them occur as small interlocking polygonal grains (plate 4.6.B).

At the locality near to Loch Coire an Daimh there is a gradual change from eclogite to QFK vein containing garnet and pyroxene. The eclogitic portion is similar to that described for SN. 353, in section 4.2 above, with segregation into pyroxene rich and garnet - quartz rich patches. There is a gradual change in the amount of QFK material present (as opposed to just quartz) from a few narrow streaks to interconnecting streaks and from this to predominantly QFK including some eclogitic material. In SN. 350b both large single garnets up to 2 mm across and patches of smaller garnet and pyroxene up to 0.5 mm across occur within the QFK streaks. The single garnets are subhedral within the QFK streaks, sometimes showing overgrowths marked by lines of tiny inclusions of sphene and quartz indicate the original garnet crystal boundaries (plate 4.2.D). The kyanite in QFK streaks occurs as elongate laths up to 0.5 mm long within the quartz and feldspar which outline a weak fabric that wraps around the large garnets and patches of eclogite. This fabric also wraps around rare patches of coarser kyanite with quartz and feldspar that have not recrystallised.

SN. 223, discussed in section 4.2.3, consists of up to 25% QFK streaks. In this rock the feldspar in the streaks is predominantly K - feldspar rather than plagioclase. Both K - feldspar and quartz occur as strained crystals up to 0.5 mm across, although some recrystallisation to form small polygonal grains has occurred. Plagioclase occurs as exsolution laminae within K - feldspar and is always present as extremely narrow rims, generally less than 0.01 mm thick, on kyanite. The kyanite is randomly orientated, often occurring as blades up to 0.25 mm across, or else as patches of symplectite with plagioclase. As in other QFK streaks, garnet is often entrained within the streaks and both this garnet and that at the vein rims is subhedral. Pyroxene is rarely found within deformed streaks.

4.2.6 Biotite - eclogite

At GR 886235, on the south coast of Loch Duich, a biotite - rich eclogite occurs, described in section 3.5 above, SN. 512. This consists of large garnet and pyroxene crystals, similar to those in the bimineralic eclogite but with stronger colours, with deep red biotite up to 2 mm across, all optically aligned, and much interstitial quartz. The biotite forms up to 20 % of the rock. Small amounts of rutile, apatite and brown amphibole also occur as crystals up to 0.5 mm across throughout the rock, generally at grain boundaries, but also as inclusions within garnet.

4.2.7 Summary of early, eclogite facies, history

Fresh specimens of all three main eclogite types contain large anhedral crystals of garnet and clinopyroxene, with or without orthopyroxene in some cases. Specimens of all types also occur in which anhedral crystals are replaced by coarse grained polygonal crystals, often associated with occurrence of quartz in garnet. Subhedral grain boundaries on otherwise anhedral crystals are also found on garnets and clinopyroxenes adjacent to primary brown amphibole and to QFK streaks. Crystals within many of the QFK streaks are also often polygonal. This change from coarse anhedral crystals to coarse polygonal crystals is similar to that described for the Western Lewisian north of Loch Duich by Barber and May (1975). The occurrence in some rocks of QFK streaks passing into polygonal garnet - quartz aggregate, e.g. in SN 223, suggests a possible link between the two.

Sanders (1988) suggested that the QFK streaks were the sites of original plagioclase, that broke down to form jadeite - rich pyroxene and quartz. However, although there is indisputable evidence for the breakdown of plagioclase, there are three main problems with that interpretation for the origin of the streaks. Firstly, the streaks occur in many different rock types, including the metapelites. Secondly, the QFK streaks are of widely differing mineralogies, all of which have similar textures and similar occurrences. Thirdly, it is suggested above, and in Sanders (1972) that there were two periods of high grade metamorphism, the first producing coarse anhedral crystals, the second slightly finer grained polygonal crystals, the latter of which also affects the QFK streaks. If the streaks were affected by two periods of high grade metamorphism, suggested by Sanders (1972) then the plagioclase within the streaks should already have broken down to form jadeite during the first metamorphism, but there is no evidence for this. Whilst some QFK streaks could well be sites of plagioclase, as suggested by Sanders (1988) that have broken down during metamorphism at high pressure and temperature, the above evidence casts doubt on whether this explanation adequately describes the occurrence of all the QFK streaks.

It is thus thought that three types of eclogite occur, bimineralic, quartz - and orthopyroxene - eclogites. The occurrence of QFK streaks appears to be related to the production of quartz - garnet aggregates in some rocks, and may be related to the occurrence of brown amphibole, with or without plagioclase and biotite in other rocks. A weak deformation (D_0) has effected all the rocks, represented in the eclogites by the alignment of slightly elongate clinopyroxene and of biotite, where it occurs, and represented in the QFK streaks by the alignment of kyanite crystals wrapping around large garnets within the streaks.

4.3 Retrogression and Deformation.

In chapter three, five deformation events were outlined. An early event (D_0) produced a weak fabric, particularly in the QFK streaks, the effects of which have already been described in section 4.2. above. Later events were associated either with the brittle deformation of the eclogite, in which the eclogite was cracked and cut by veins; with cataclasis, involving mylonitisation of the eclogites; or with ductile deformation and alteration of garnet and pyroxene to produce predominantly hydrous assemblages characteristic of lower pressures and temperatures. These later deformation events are termed D_1 - D_4, discussed in chapter two. On the whole they produce a change from coarse grained anhydrous rocks to fine grained hydrated rocks.

4.3.1 Retrogression without deformation

Retrogression has affected almost every sample of eclogite to a greater or lesser extent. Even in fresh rocks there is almost always some slight alteration with dusty cores occurring within many clinopyroxenes.

Initial alteration of the clinopyroxene occurs with the growth of symplectites of clinopyroxene and plagioclase. In general this occurs at grain boundaries, with concoidal areas of symplectite growing in from the original clinopyroxene grain boundary. More rarely symplectite occurs alongside cracks where these cracks cut clinopyroxene, but these same unfilled cracks do not alter either garnet or primary brown amphibole. In this case, the symplectite is extremely fine grained closest to the crack, and progressively coarser away from the crack. The growth of symplectite appears to occur in at least two stages, forming a coarse intergrowth at first, and later a fine intergrowth, although it is possible that symplectites grew at different stages of retrogression in different rocks. In rare rocks the clinopyroxene is almost entirely altered to both coarse and fine symplectite with little or no alteration to garnet (or brown amphibole).

Initial alteration of both garnet and brown amphibole occurs with the growth of a thin rind of amphibole at grain boundaries. This amphibole is pleochroic from blue green to dark green to pale greenish yellow (plate 4.3.D). Occasionally it appears to form between adjacent clinopyroxene crystals, themselves partly altered to symplectite.

These alterations represent the maximum state of retrogression of fresh eclogites, although most show little alteration.

In rocks where retrogression has occurred to a greater extent, relicts of garnet are common, but pyroxene relicts are rare. Symplectites of clinopyroxene and plagioclase are altered to form a symplectite of green amphibole and quartz, with either plagioclase or clinopyroxene relicts (plate 4.4.A). Often this amphibole is recrystallised to form large crystals up to 2 mm across with many small inclusions of quartz, termed sieve amphibole. Rocks at this state of alteration are often cracked, with the cracks being filled by plagioclase and amphibole. Sometimes this alteration occurs as wide zones of coarse - grained amphibole and plagioclase that completely replaces the eclogitic minerals and textures. Synchronous with the growth of amphibole and plagioclase is the growth of plagioclase moats, either around all minerals or more commonly between garnet and quartz (plate 4.8.A). These plagioclase moats are very common, and are found in samples from most outcrops of the Eastern Lewisian eclogite. They probably occur due to reactions of the form Gnt + Cpx + Qtz + $H_2O \Rightarrow$ Pl + Amph, e.g. (for CMASH) :

$$3CaMg_2Al_2Si_3O_{12} + 2CaMgSi_2O_6 + 3SiO_2 + 2H_2O \Rightarrow CaAl_2Si_2O_8 + 2Ca_2Mg_4AlSi_7AlO_{22}(OH)_2$$

Further alteration is generally, but not always, related to deformation. In rare rocks garnet is altered at grain rims to intergrowths of epidote and amphibole, or more rarely to just epidote. Amphibole occurs as coarse grained dark - green, inclusion - free crystals. Quartz and feldspar are common throughout the rock.

The exposure of orthopyroxene - eclogite SN. 223 is affected slightly differently. In SN. 223 itself there is only minor alteration, with the retrogression of clinopyroxene to a very fine grained symplectite at rims of QFK streaks. No alteration occurs alongside cracks in the rock. In more altered samples from the same outcrop, such as SN. 224, clinopyroxene is altered at grain boundaries to the same fine symplectite, although patches of unaltered pyroxene do remain. In cracks and at the rims of crystals, garnet is altered to green biotite, but close to small rutile crystals, garnet is altered to brown biotite (plate 4.4.B). Orthopyroxene is altered to patches of talc and colourless amphibole. Both SN.'s 223 and 224 are cut by cracks filled by plagioclase and actinolite, with little alteration of the rock at the edges of the cracks. In still further retrogressed samples, such as SN. 342, the garnet has altered first to form moats of plagioclase between it and the surrounding amphibole - quartz symplectite, and is then replaced by chlorite. This results in a rock consisting of patches of chlorite with rare cores of garnet, sitting in moats of plagioclase, and of talc and colourless amphibole after orthopyroxene all enclosed in a mesh of fine grained symplectite after clinopyroxene. For comparison with the retrogression of QFK streaks, to be discussed in section 4.4.6 below, alteration of kyanite in SN. 224 is to margarite, whilst in SN. 342, which has undergone more extensive retrogression, it is to muscovite.

4.3.2 Cataclasis

Cataclasis has affected many of the basic rocks of the Eastern Lewisian within discrete bands (Sutton and Watson, 1959). This has affected both eclogites and apparently already partly retrogressed rocks. With the eclogites there has been extreme granulation of eclogite facies minerals, but without alteration (SN. 217). Clinopyroxene is most susceptible, forming fine - grained aggregates of polygonal crystals around relict strained, anhedral cores. Garnet is usually unaffected, although it is occasionally partly recrystallised to form fine, polygonal crystals up to 0.05 mm across (plate 4.3.A). The QFK streaks within this rock are recrystallised as parallel - sided streaks, with kyanite oriented along the streaks, and with quartz and feldspar both occurring as both large, strained porphyroblasts and as extremely fine - grained granules. Some rocks appear to have been partly retrogressed prior to cataclasis with garnet, pyroxene, green - amphibole and plagioclase all occurring as coarse porphyroblasts up to 0.25 mm across in a very fine - grained matrix of amphibole and plagioclase. The clinopyroxene is commonly altered to form sieved amphibole, whilst garnet is often altered to intergrowths of epidote and amphibole.

Cataclasis has also affected fully retrogressed rocks. Although some show traces of original garnet and clinopyroxene, with occasional sieved amphibole or knots of epidote and amphibole, many consist only of inclusion - free porphyroblasts of amphibole and plagioclase in a matrix of extremely fine grained quartz, feldspar, epidote, biotite and amphibole. There is a distinct compositional layering into hornblende and plagioclase rich layers.

All the rocks that have suffered cataclasis are invariably cut by cracks filled with epidote, plagioclase and calcite.

4.3.3 Brittle Deformation

In some eclogites alteration only occurs alongside cracks across the rocks. These cut all the high - grade minerals described in section 4.2 above. Cracking of the rock has occurred on at least three different occasions, with different mineralogies growing within the cracks on each occasion. Some rocks contain unfilled cracks, alongside which the host rock remains unaltered.

As already mentioned above, the earliest cracks produced a fine grained symplectite across pyroxene but no alteration occurs to garnet or brown amphibole (plate 4.3.C). Any biotite recrystallises to form small crystals parallel to the cracks. This symplectite becomes finer grained away from the crack (plate 4.7.D). Amphibole - plagioclase filled cracks were also mentioned.

Further cracking occurs within the eclogite, usually filled by epidote - amphibole - plagioclase (plate 4.8.B). Alteration of previously unaltered eclogite at the rims of these cracks is restricted, although occasionally pyroxene alters to symplectite and garnet to epidote and/or amphibole. The veins also cut across much of the retrogressed eclogite described in the previous paragraph. Some patches of already altered eclogite suffer further retrogression with the alteration of the remaining garnet to a symplectite of epidote and amphibole.

The last set of cracks to affect the rocks cut across all of the above and are filled by chlorite - calcite - plagioclase, with little alteration at the crack rims. Chlorite tends to grow where the cracks cut garnet, whilst calcite and plagioclase occur where they cut pyroxene and amphibole.

In orthopyroxene - bearing eclogites the sequence of retrogressive events is similar to the other eclogite types, but the cracks are often filled by different mineralogies. In SN. 511, described in section 4.2.3 above, there is very little alteration, restricted to two generations of cracks. The first set of cracks are filled by green amphibole with rare calcite, which alters both ortho - and clinopyroxene at the crack rims. This alteration occurs on a variety of scales, varying from a thin rind to the cracks, to up to 2 mm of alteration either side of a crack. Where the cracks cut orthopyroxene there is alteration to talc and iron oxide. Garnet in the orthopyroxene is altered to iron oxide. The second set of cracks are filled by actinolite and have no alteration at the crack rims. SN. 337 is also generally unaltered and affected by only one set of cracks, in this case filled by epidote and actinolite. Alteration at the rims of cracks is rare, although a few cracks have alteration rims up to 1 mm across. In these the orthopyroxene alters to a fine intergrowth of talc and iron oxide. Garnet is altered to epidote and pyroxene to pale amphibole. The other, orthopyroxene - free, eclogites from the same exposure contain three sets of cracks; amphibole - filled cracks; epidote - actinolite filled cracks; and stilpnomelane - filled cracks that often have an offset across them, well seen in SN. 218.

4.3.4 Ductile deformation

Ductile deformation of the eclogite and its associated retrogression has occurred in a number of steps. After each step some relict rocks are then deformed further in a brittle manner, and are cut by cracks similar to that described above, rather than in a ductile manner.

There appears to be a complete transition from mylonitised rocks affected by cataclasis in which minerals have been ground down without being recrystallised, to strongly foliated, fine - grained rocks, consisting mostly of a matrix of tiny, slightly elongate amphibole, plagioclase and rarely biotite crystals, including sieve amphibole after pyroxene, to produce a weak texture wrapping around coarser garnet and amphibole porphyroblasts (plate 4.8.C). The garnets within these rocks remained rigid and tended to crack, with many of the cracks filled by chlorite or plagioclase. Some of the garnets in these more deformed rocks show features similar to those outlined in section 4.3.1 above, with narrow lines of sphene and quartz inclusions outlining cores and overgrowths of garnet. In some samples, e.g. SN. H4, there are no larger porphyroblasts, the entire rock made up of elongate, fine - grained amphibole and plagioclase.

Some folds, e.g. SN. 510, from outside Hazel Brae, have a lineation parallel to the hinge axis, and fold a weak foliation. In section 3.7 these were interpreted as being of D_2 age, folding a D_1 fabric. This fabric is outlined by compositional layering into hornblende - rich and quartzo - feldspathic rich layers. It resembles deformed migmatites seen in the Western Lewisian (chapters 7, 8). The fabric consists of stubby green amphibole crystals and elongate green - brown biotite crystals, subhedral epidote and sphene. Both the latter contain small inclusions of quartz. Plagioclase and quartz occur as large polygonal crystals, and the plagioclase is often dusty. The mafic minerals, particularly biotite, are recrystallised so that they are subparallel to the hinge.

Many of the folds fold strongly foliated rocks, and deform a lineation. SN. H4 consists of green amphibole which is smeared out to produce extremely attenuated crystals, often up to 2 mm long, but only a fraction of a mm across. Quartz, feldspar and epidote form polygonal crystals. Often there has been segregation to produce amphibole - epidote layers, and pure quartz - feldspar layers. The folds are tight brittle folds, with cracking of the amphibole at fold hinges. These folds were interpreted as being of D_3 age in section 3.7. above (plate 4.4.D).

Pods of almost pure, coarse - grained, interlocking amphibole occur sporadically throughout the Eastern Lewisian, and are fairly common south of Fern Villa, similar to the "amphibolitite" described in the Western Lewisian (chapters seven, eight). These do not appear to have been eclogites and are described more fully in chapter six.

4.3.5 Summary of retrogression

The structural history outlined in chapter two involved four deformation events after Moine deposition. The first, D_1, involved interleaving of Moine and Lewisian rocks. The second, D_2, involved folding and shearing along slide zones. The third, D_3, involved further folding.

The general retrogression of the eclogites begins with the alteration of clinopyroxene to form symplectites of plagioclase and diopside. Further alteration then converts the rocks into garnet - amphibolites, with diopside - plagioclase altered to sieved amphibole - large single crystals of amphibole filled with quartz inclusions, and with garnet partly altered to amphibole and plagioclase. Surviving garnet is relict eclogite - facies garnet. The final alteration occurs to produce epidote and amphibole from the remaining garnet to produce and epidote - amphibolite. Each stage of alteration appears to be related to a period of deformation. In fresh eclogite in which garnet and clinopyroxene have not been altered, the same series of alteration events can never - the - less be seen in narrow cracks. Early cracks lead to alteration of clinopyroxene. Later cracks alter garnet and clinopyroxene to plagioclase and amphibole. A later set of cracks still are filled with epidote, plagioclase and actinolite. In chapter three is was inferred that these occurred pre - or syn - D_2 and D_3 respectively.

Growth of clinopyroxene symplectites probably occurred on at least two different occasions, with coarse - and fine - grained symplectites occurring. As fresh clinopyroxene is seen in the rocks after all the phases of deformation, this alteration to produce symplectite may have occurred at almost any time in the rock's history. However, it is likely that much of the alteration to produce symplectites occur post - Cataclasis, as sieved amphibole after clinopyroxene occurs within the mylonites. This raises the problem of the nature of D_1 deformation and of why the rocks were not retrogressed during their initial uplift prior to Moine - deposition. It may be that many of the mylonites actually represent pre - Moine deformation that has been re - activated during D_2 events, especially as field evidence outlined in chapter three suggests that the eclogites were deformed prior to D_1.

Much of the deformation required to form the parallel banding between the Moine and the Lewisian was interpreted by Sutton and Watson (1958) as being during D_1. It is likely that the pods of eclogite found throughout the Eastern Lewisian were formed during this time and that during D_2 the eclogites and some of the deformed rocks were cracked, with the cracks filled by, and altering eclogite alongside to, plagioclase and amphibole, although the cracks may have formed during D_1 and been filled during D_2.

4.3.6 Retrogression of quartz - feldspar - kyanite streaks

In section 4.2.4, above, the initial occurrence and metamorphism of the QFK streaks was described.

In many of the QFK streaks cracking that led to the growth of plagioclase and amphibole in the eclogites has produced no retrogression. Cracks filled by epidote and pale amphibole cut both the eclogite and the QFK streaks. This cracking has been described in the eclogites above.

Where alteration does occur, it is limited to the retrogression of kyanite to zoisite at the crack margins. In SN. 83, described in detail in section 4.3.1 above, large kyanite crystals are altered to a thin rind of either white mica, or of zoisite. Garnet has been altered to green amphibole where it is in contact with plagioclase, but in contact with quartz it appears to remain stable. Symplectites of biotite - quartz occur, possible after garnet. Plagioclase tends to be dusty, and in part altered to scapolite. SN. 350b is more representative of the QFK streaks. Entrained pieces of pyroxene are usually altered to a fine grained symplectite of amphibole - plagioclase, with unaltered pyroxene only occurring as garnet inclusions. Garnet is usually altered to a thin rind of epidote - amphibole, although it is also more rarely altered to chlorite or to amphibole - plagioclase, similar to alteration seen around veins cutting across garnet within the eclogite. Sometimes garnet remains without an alteration rim. In places garnet alters to plagioclase. Usually this produces patches of plagioclase - garnet symplectite, but in one extreme case (SN. 350b) produces small irregular garnet fragments in a matrix of plagioclase polygons.

Kyanite within QFK streaks is altered variously to zoisite, margarite, muscovite and plagioclase. Initial alteration of the kyanite produces plagioclase rims. Even in otherwise unaltered streaks, such as in SN. 223, kyanite always has these rims. Alteration to produce margarite between plagioclase and kyanite is common, occurring in most rocks. By correlation between the retrogression seen within basic rocks and QFK streaks within them, it is probable that margarite growth occurred at a similar time to the growth of sieved amphibole from diopside - plagioclase symplectites, thought to be pre - D_1. Similarly, later alteration of kyanite and/or margarite produces either muscovite or zoisite, thought to occur syn - Moine deformation and metamorphism, probably during D_2. The last three processes all require water. The reactions involved will be discussed in chapter 5. In SN. 80, a retrogressed and deformed version of SN. 83, small patches of plagioclase - quartz - zoisite still remain within the surrounding epidote - amphibole - plagioclase rock. Small amounts of epidote and amphibole often occur in completely retrogressed QFK streaks due to the initial presence of entrained garnet and pyroxene (plate 4.9.A).

In many of the streaks there is segregation into patches of quartz and of feldspar - kyanite (plate 4.9.B). It is probable that this happened early on in the history of the QFK streaks as in many cases kyanite is either unaltered, except for a plagioclase rim, or is altered to margarite. In SN. 233 the streaks consist of blotchy quartz rich patches, and kyanite - plagioclase patches.

4.4 Conclusions

Fresh eclogite is ubiquitous, but only occurs where rocks have remained dry. During late deformation, hydration occurred forming amphibolite and epidote - amphibolites. There are a number of related eclogite types, the mineralogy probably dependant upon the bulk composition of the rock, although it is possible that the intrusion of QFK material into the rocks prior to high - grade metamorphism produced some of the variety seen in the eclogites, namely brown - amphibole or biotite rich eclogite with or without plagioclase, and eclogites with garnet - quartz aggregates. Sanders (1988) suggested that these QFK streaks represented the sites of original plagioclase in the igneous precursor to the eclogites.

Eclogite facies metamorphism probably occurred on two occasions, the first producing coarse anhedral crystals, the second producing coarse interlocking polygonal crystals, and in which some rare hydrous phases, such as brown amphibole, are stable, and in which plagioclase within QFK streaks altered to kyanite - bearing assemblages.

There are five deformation events. The earliest (D_0) has affected the eclogites after the intrusion of the QFK streaks, leading to widespread recrystallisation of rocks with a marked fabric, although the effects of this event are not easily identified in thin section. The next three events (D_1 - D_3) have affected the rocks after partial hydration and alteration of the eclogites. Although in chapter two the D_2 event was interpreted as producing mylonites, after May *et al.* (1993), Sutton and Watson (1958) argued that the first of these events (D_1) formed the mylonites within the eclogites, and produced the parallel structures seen in the Moine and the Lewisian. The D_1 deformation may well have been responsible for the parallel layers in the Lewisian and even some mylonites, with later deformation possibly only accentuating these effects. On the whole, during each deformation event the unretrogressed, dry, eclogites reacted in a brittle manner to the deformation events and were cracked. The retrogressed, wet, equivalents were deformed in a ductile manner. In both cases, the stable mineralogy in each situation is the same, being plagioclase - amphibole and garnet during D_2 and epidote and actinolite during D_3, with the previous eclogite facies mineralogy being metastable. In the QFK streaks, margarite is an early alteration product of kyanite. Later, during D_2 deformation, zoisite and/or muscovite are stable.

Plate 4.1.

A) Bimineralic eclogite (SN. 265). Coarse garnet (pink) and clinopyroxene (pale green). Limited alteration of pyroxene at rims to a fine grained symplectite. Small amounts of dark green amphibole, pale brown biotite, and dark rutile. (field of view : 16 mm).

B) Clinopyroxene within coarse garnet (SN. C4). Crystals are subhedral. Minor alteration has occurred at pyroxene rims to produce brown amphibole. (field of view : 15 mm).

C) Alteration of bimineralic eclogite to quartz - eclogite (SN. 353). Interlocking clinopyroxene (right) passes into clinopyroxene and quartz (centre). (field of view : 9 mm).

D) Coarse clinopyroxene in orthopyroxene - eclogite (SN. 223) with rutile inclusions surrounded by fine grained polygonal clinopyroxene. With smaller, high relief, garnets and fine grained biotite. Centre top : edge of QFK vein. (field of view : 8 mm).

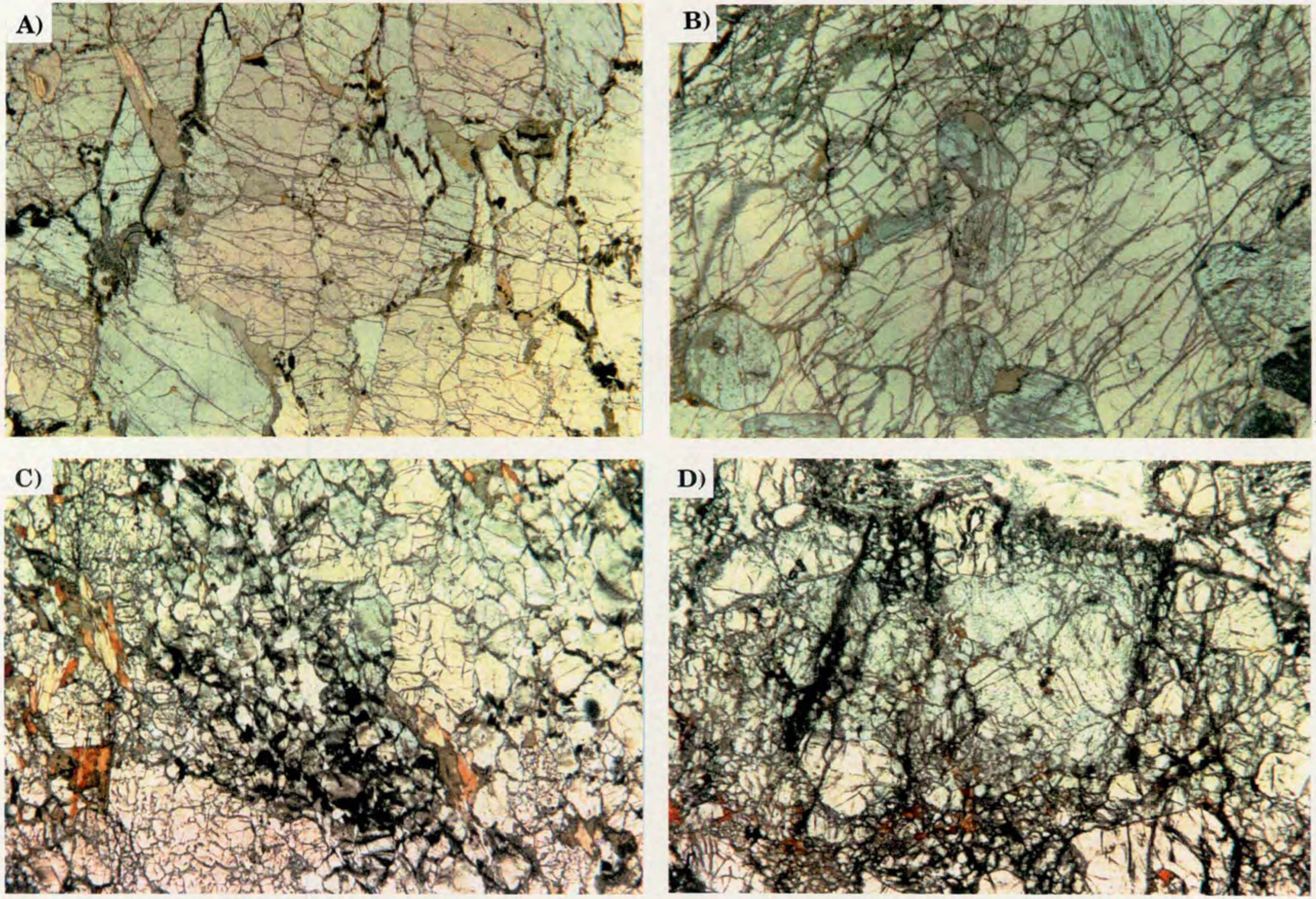
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Plate 4.2.

A) (in crossed - polars) Garnet in orthopyroxene - eclogite (SN. 223) cut by the continuation of a QFK vein. Garnet is recrystallised as fine - grained polygonal garnet with tiny quartz inclusions. (field of view : 7 mm).

B) Orthopyroxene - eclogite (SN. 337). Coarse pink garnet and finer pale green pyroxene, with high relief orthopyroxene, outlined by black alteration rims of iron - oxide. Cracks are filled by actinolite. (field of view : 12 mm).

C) Fine - grained bimineralic eclogite (SN. 218, from outcrop of orthopyroxene - eclogite SN. 337) with large patch of QFK containing entrained garnets. Both parts are heavily cracked. In the eclogitic portion the cracks are filled by amphiboles and stilpnomelane. In the QFK they are filled by zoisite. (field of view : 26 mm).

D) Garnets within QFK rich portion of quartz - eclogite (SN. 350b). Large subhedral garnets are entrained within the QFK veins. The remnants of clinopyroxene occur as fine grained dark green amphibole - quartz symplectites. Some rutile (brown) and biotite (pale brown) occur. Kyanite forms elongate lathes within the quartzo - feldspathic matrix. These are almost all altered to margarite and zoisite. (field of view : 6 mm).

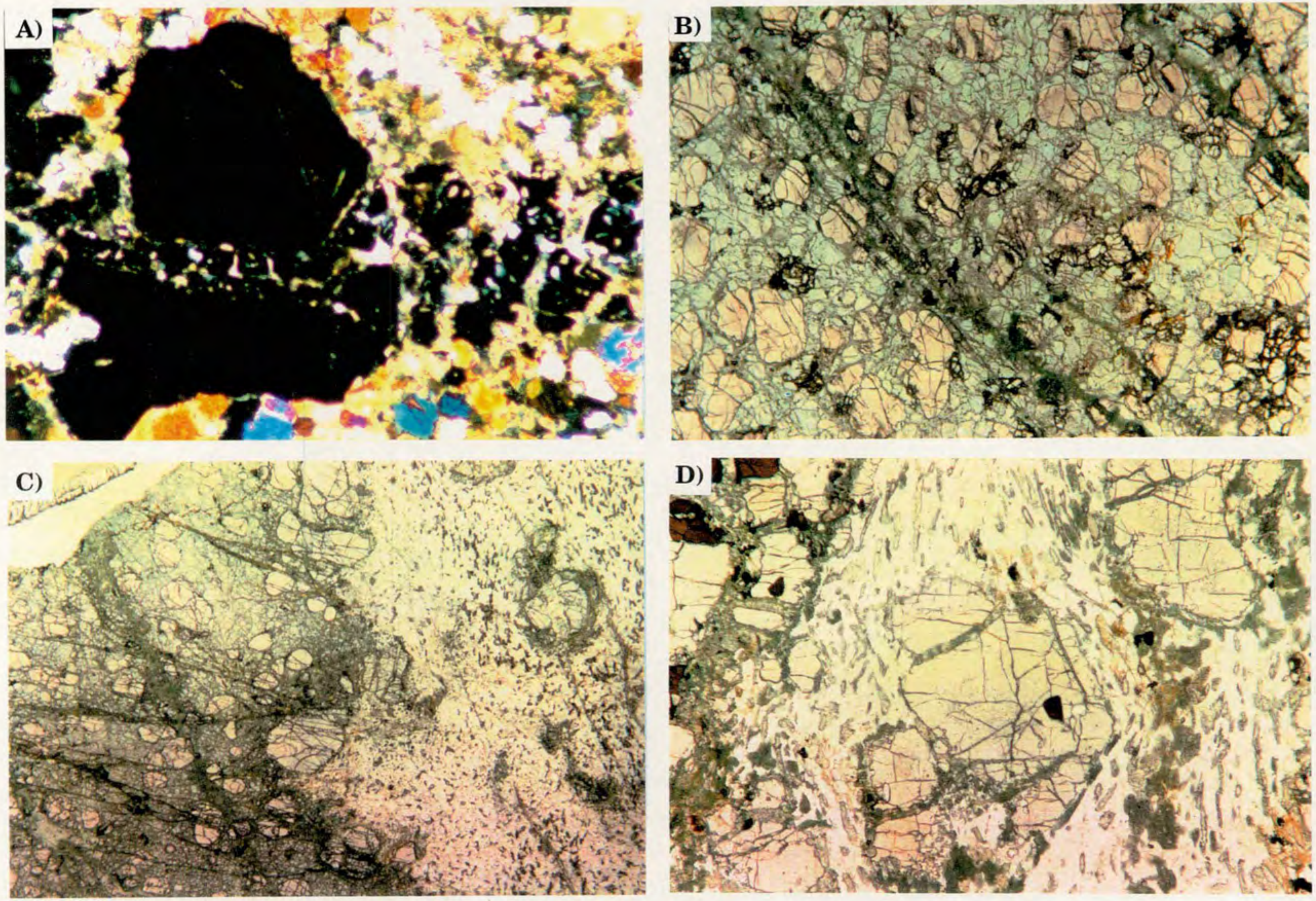
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Plate 4.3.

A) Bimineralic eclogite (from outcrop of orthopyroxene - eclogite, SN. 337) with relicts of coarse anhedral clinopyroxene recrystallised at grain boundaries to fine - grained interlocking polygonal clinopyroxene. (field of view : 5 mm).

B) Quartz - eclogite (SN. 83). Coarse cracked garnets with finer grained clinopyroxene, rutile and quartz. (field of view : 6 mm).

C) Bimineralic eclogite with some alteration to produce coarse brown - green amphibole (SN. E9). Garnet, clinopyroxene and amphibole are cut by cracks. Only clinopyroxene is altered, to fine symplectite with plagioclase. (field of view : 23 mm).

D) Retrogressed bimineralic eclogite (SN. E3). Relict garnet (pale), symplectite after clinopyroxene (dark) and brown amphibole, cut by two generations of cracks. One left - right is filled with pale green amphibole. The other, top - bottom, is filled by calcite and feldspar. (field of view : 20 mm).

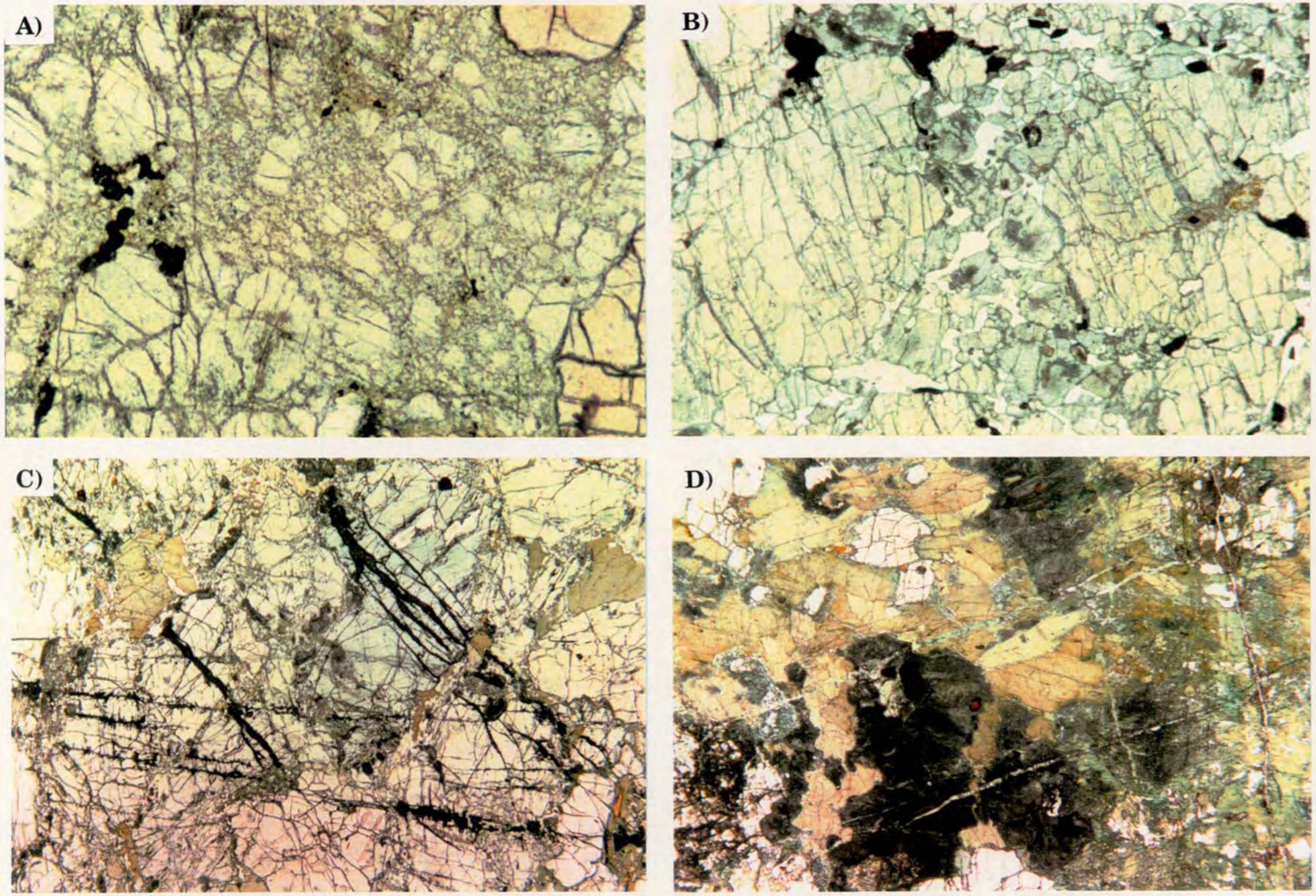
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Plate 4.4.

A) Alteration of clinopyroxene (SN. 129). Omphacitic clinopyroxene has altered to a symplectite of mid - green diopside - rich pyroxene with plagioclase. This is partly altered to a coarser symplectite of dark green amphibole and quartz. (field of view : 3 mm).

B) Altered orthopyroxene eclogite (outcrop of SN. 223). Subhedral garnet (heavily cracked) and anhedral clinopyroxene (tiny inclusions) remain in a fine grained ground mass of symplectite after clinopyroxene. Alteration has occurred most along QFK vein boundaries. Lathes of kyanite within the QFK veins are mostly altered to margarite. (field of view : 11 mm).

C) Mylonitised eclogite (SN. Du4). Relict coarse garnet (pale) and symplectite after clinopyroxene (darkest green) within a matrix of fine - grained amphibole, feldspar and quartz. (field of view : 14 mm).

D) Folded amphibole - rich rock from Hazel Brae (SN. H4) (see plate 3.6.B). Extremely elongate amphiboles are gently folded, and cracked sub - parallel to the hinges. Cracks are filled by K - feldspar and stilpnomelane. (field of view : 16 mm).

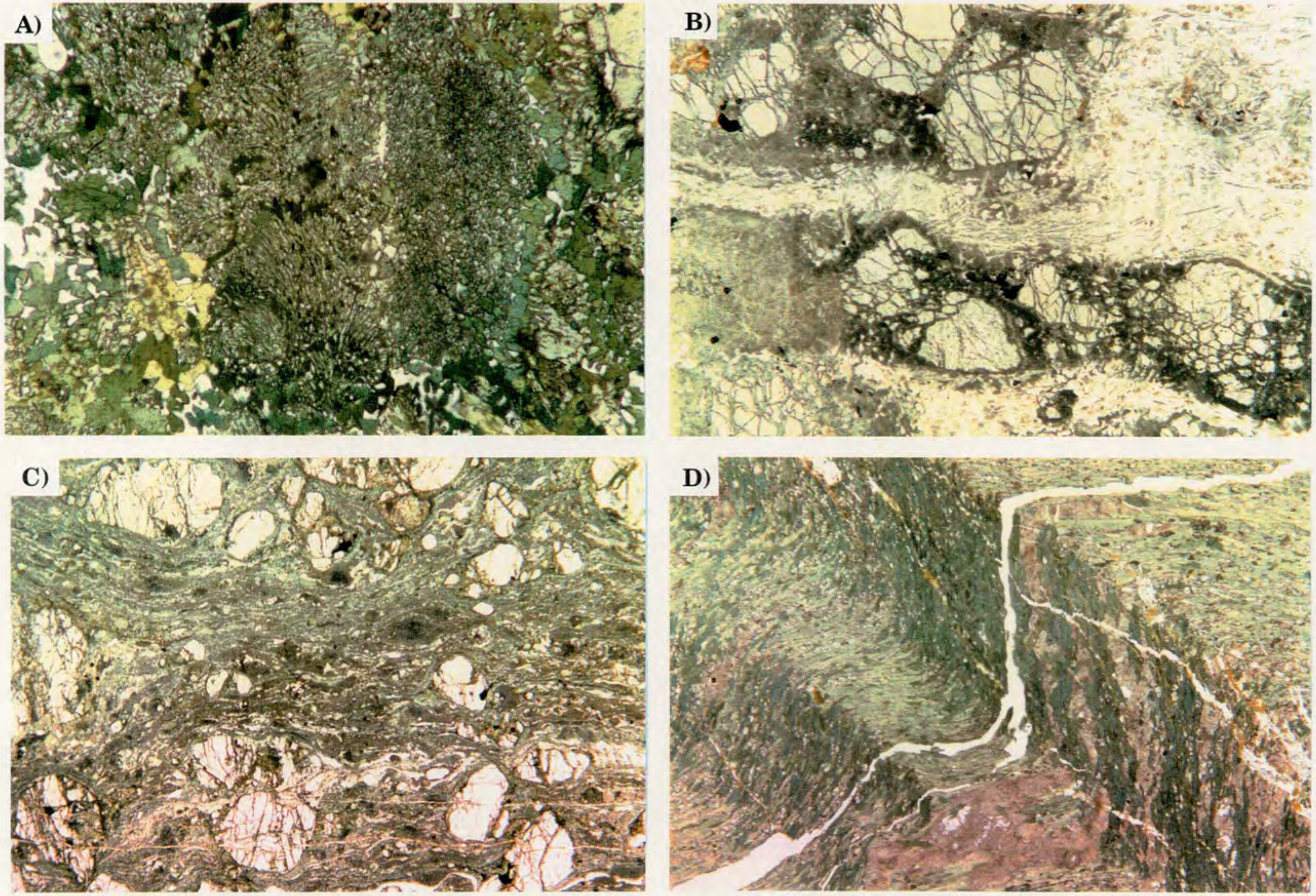
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Plate 4.5.

A) Quartz - eclogite (SN. 353) with fine grained polygonal garnet riddled by inclusions of quartz, occurring with brown amphibole and biotite (both dark). (field of view : 3 mm).

B) Small polygonal garnet with rare quartz and rutile inclusions at the rims of a QFK vein (SN. 353). (field of view : 3 mm).

C) Orthopyroxene in SN. 511 (high relief), with laminae of garnet (pale, within opx). Both are cut by cracks, filled by iron oxide. Pale crystals left and right are clinopyroxene. (field of view : 3.5 mm).

D) (in crossed - polars) Clinopyroxene from SN. 511. (pale) with irregular laminae of garnet, and sphene inclusions. (field of view : 2 mm).

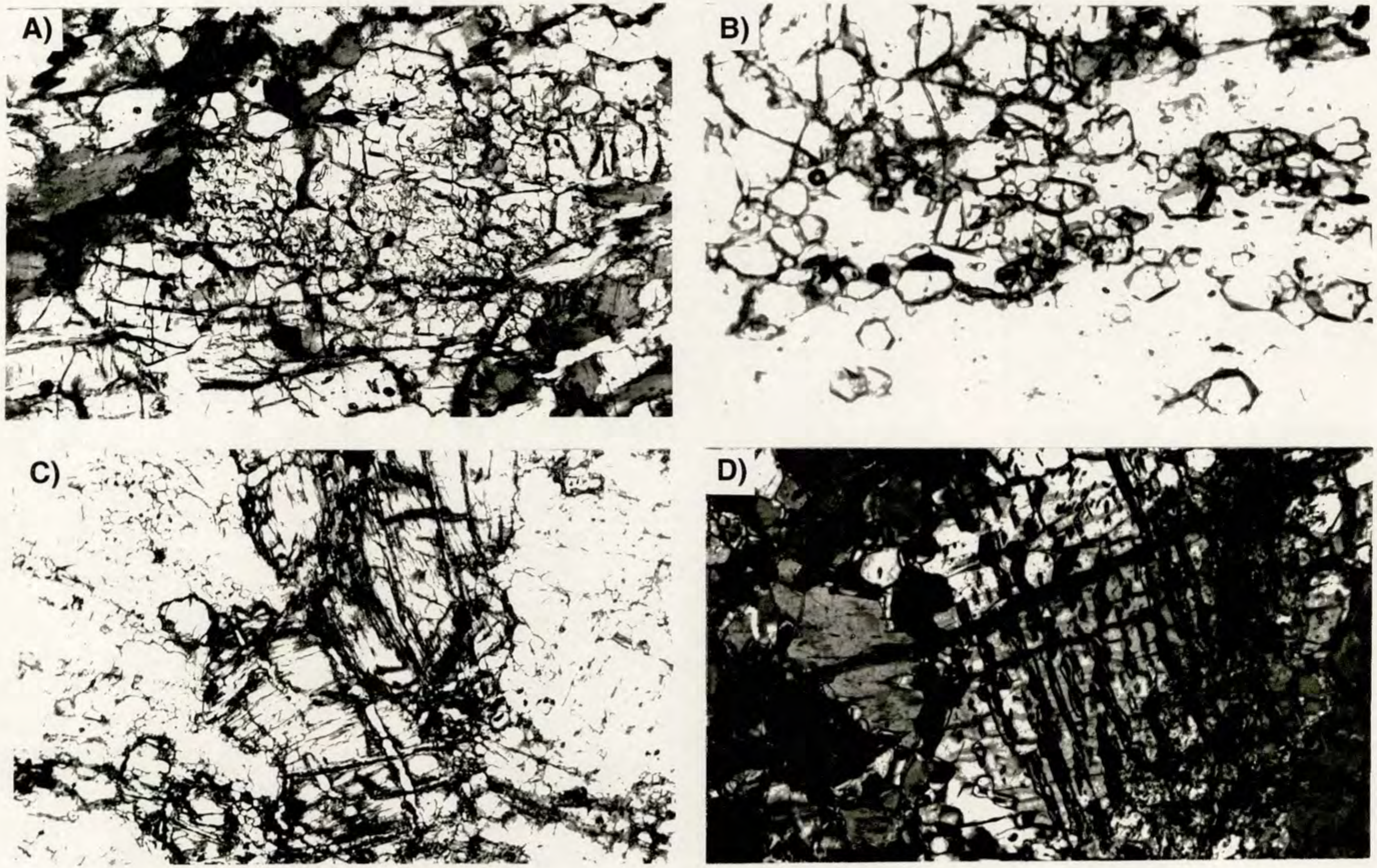
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Plate 4.6.

A) Rim of clinopyroxene (SN. 511). Anhedral clinopyroxene with elongate inclusions of sphene is rimmed by polygonal crystals of garnet riddled with inclusions of quartz, opaques and biotite. (field of view : 2.5 mm).

B) Bimineralic eclogite cut by QFK veins (SN. 217). Veins of QFK rock cut the eclogite, with entrained subhedral garnets. Kyanite blades are orientated along the length of the vein. The rock is cut by two generations of cracks, one filled by dark amphibole with little alteration, the other by epidote - actinolite with much alteration. (field of view : 25 mm).

C) Rim of large brown amphibole within bimineralic eclogite (SN. E9). At the rim amphibole has a coarse symplectite with plagioclase. Bottom right : part of clinopyroxene. (field of view : 2.5 mm).

D) Coarse biotite - plagioclase symplectite from bimineralic eclogite (SN. E2). (field of view : 2 mm).

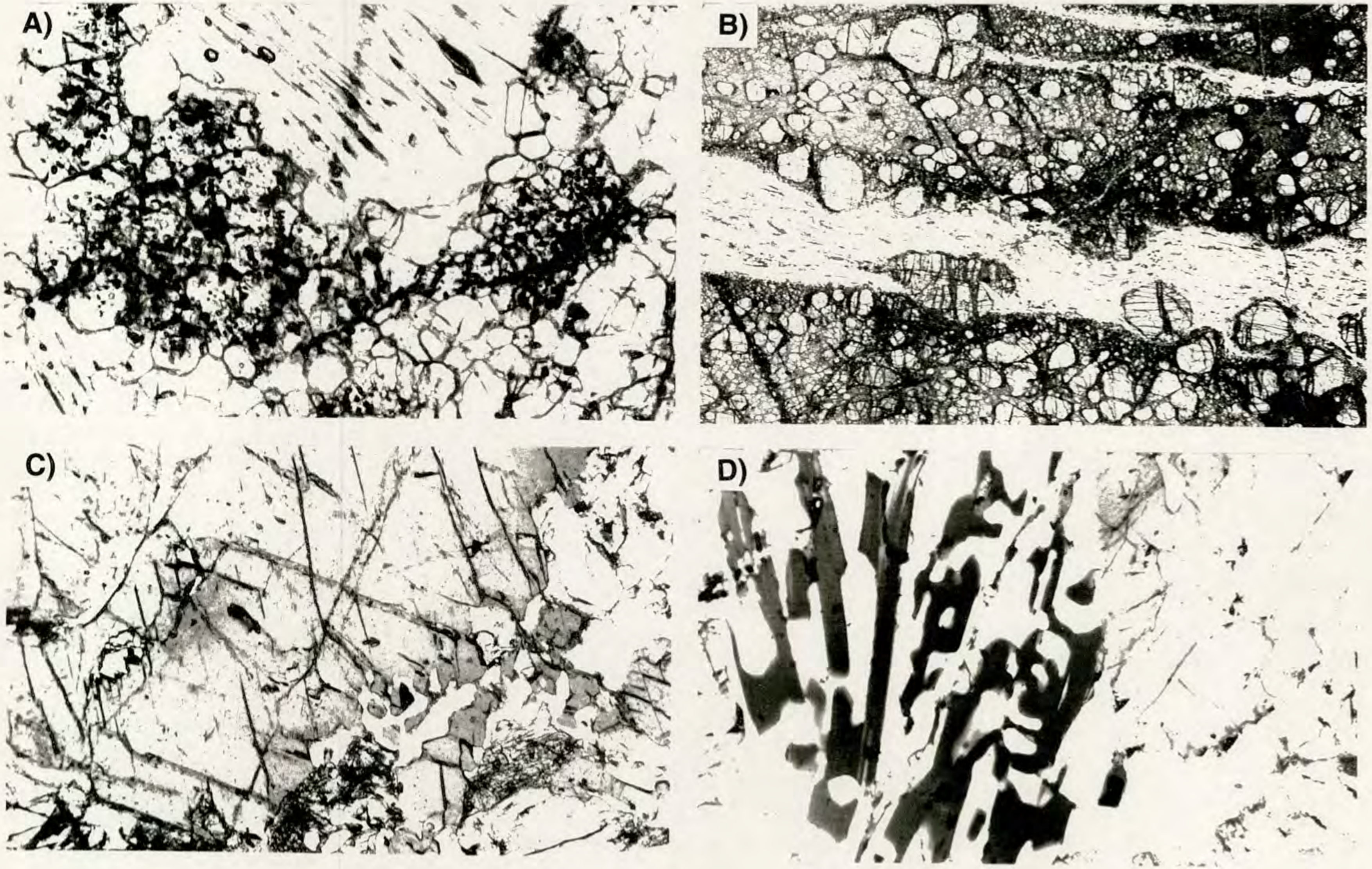
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Plate 4.7.

A) Eclogite with QFK veins (SN. 96). All the major crystals are polygonal in both eclogite (dark) and vein (pale). Kyanite forms stubby crystals between polygonal quartz - feldspar. (field of view : 9 mm).

B) (in crossed - polars) Garnet in quartz - eclogite with inclusions of quartz and sphene outlining a subhedral core and an anhedral overgrowth (SN. 83). (field of view : 2 mm).

C) Coarse kyanite (high relief) within quartz - eclogite (SN. 83). Rims are altered to muscovite. Other dark minerals are biotite, rutile and iron oxide. (field of view : 4 mm).

D) Close up of symplectite alongside cracks across clinopyroxene within bimineralic eclogite (SN. E9) (see plate 4.3.C). The centre of the crack is extremely fine - grained plagioclase and clinopyroxene, the edges of the crack are of fairly fine symplectite. Either side is unaltered clinopyroxene (pale). (field of view : 2 mm).

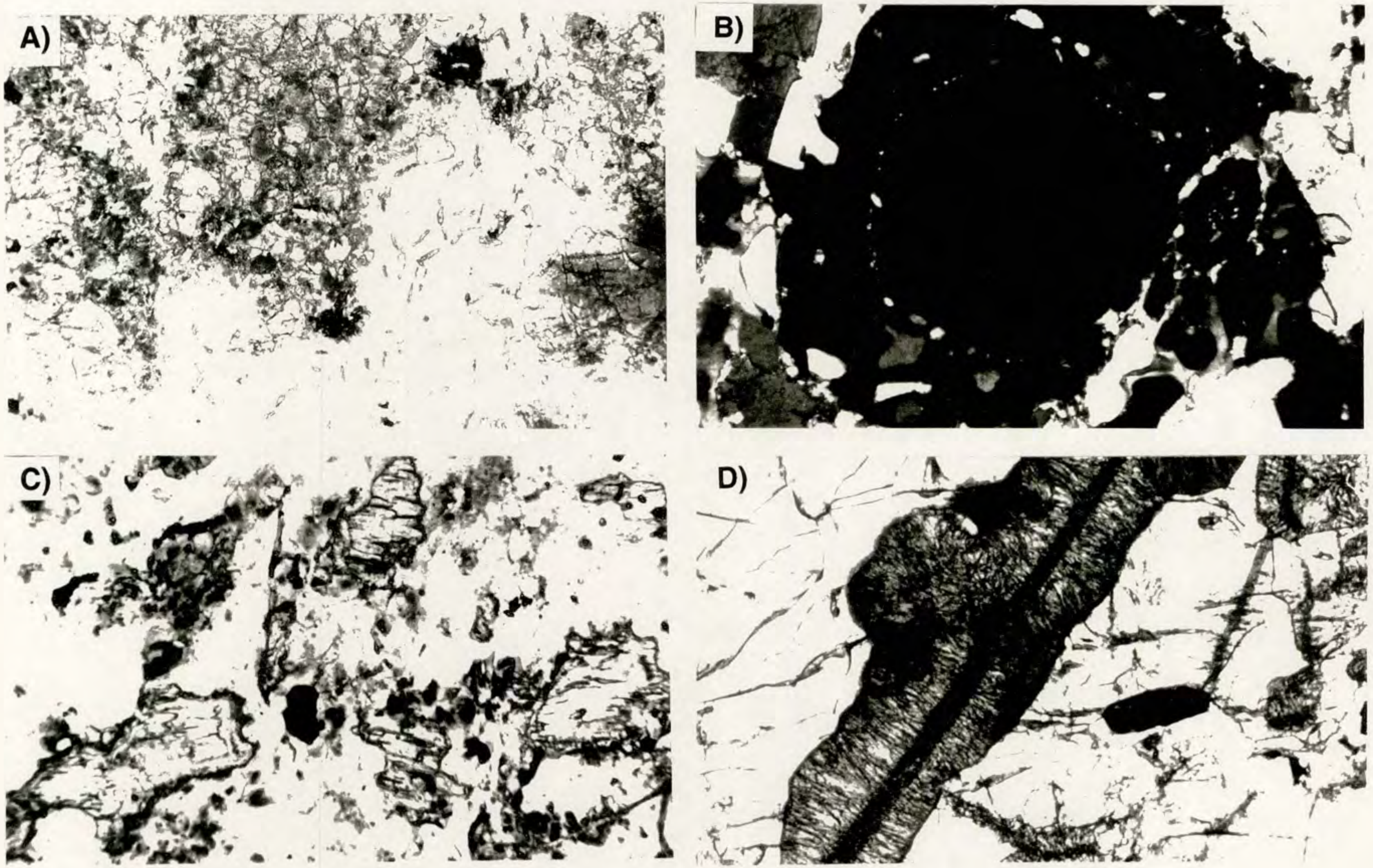
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Plate 4.8.

A) Bimineralic eclogite with garnet (pale, high relief) clinopyroxene (messy), rutile (dark) and quartz (pale, low relief) (SN. 512). All minerals are surrounded by a thin sheath of plagioclase, except between quartz and garnet, where there is also amphibole. (field of view : 8 mm).

B) Filled cracks across eclogite, best seen across brown amphibole (dark), altered to pale amphibole where cracked (SN. 353). (field of view : 2 mm).

C) Fine grained garnet - amphibolite, with small rounded garnets (pale) in a schistose matrix of amphibole, plagioclase and quartz (SN. 82). (field of view : 25 mm).

D) Garnet (pale, high relief) within garnet - amphibolite, altered to chlorite along cracks, and to epidote and hornblende at the rims (SN. 40). (field of view : 1.5 mm).

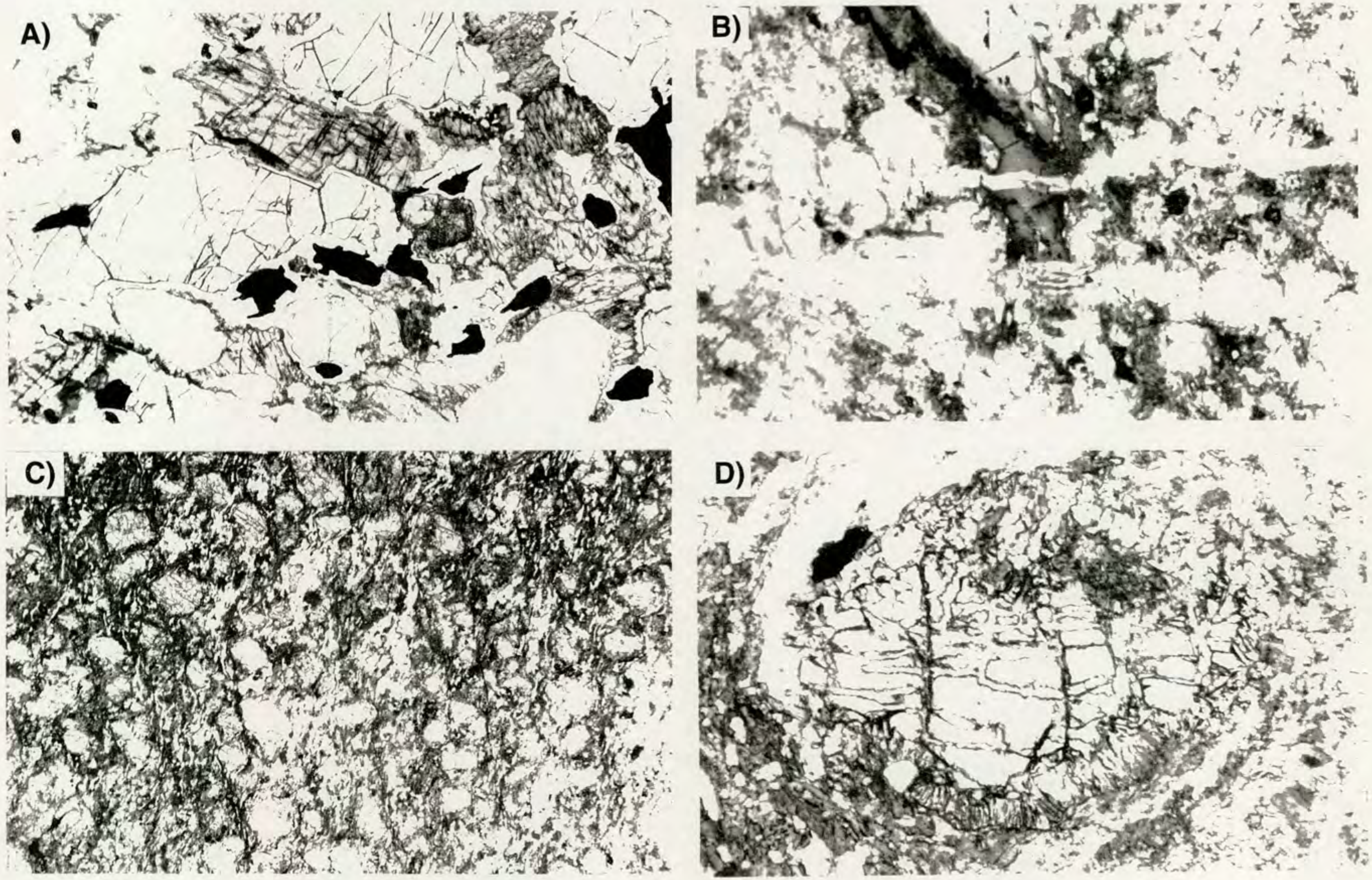
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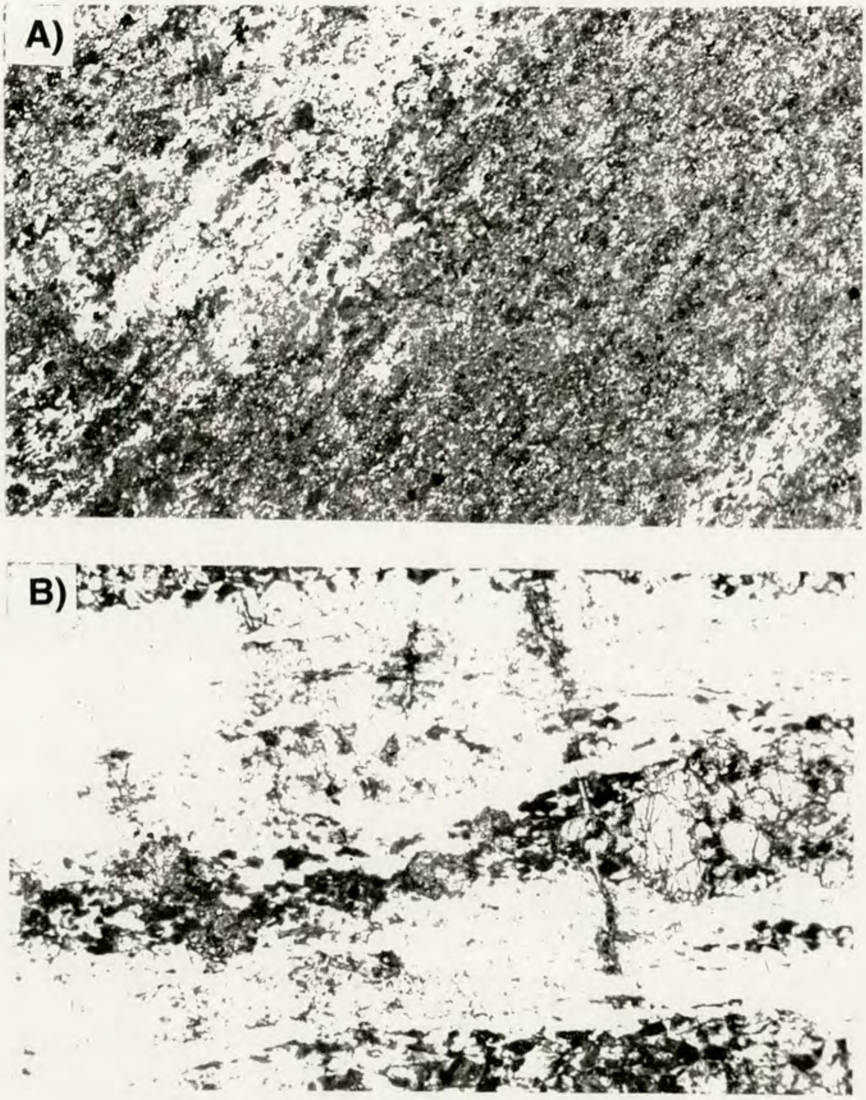
Plate 4.9.

A) Amphibolite of amphibole, plagioclase and quartz (darker areas) and relict QFK patches, with quartz, plagioclase and zoisite (pale) (SN. 81) (field of view : 13 mm).

B) Segregation of QFK veins into elongate quartz patches (clean) and plagioclase - kyanite patches (dirtier) (SN. 351). The latter are partly altered to scapolite and zoisite respectively. Dark patches are eclogitic. Cracks filled by epidote cut across everything. (field of view : 14 mm).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Chapter Five

Geochemistry of the Eastern Lewisian eclogites and related rocks

CHAPTER 5

Geochemistry of the Eastern Lewisian eclogites and related rocks.

5.1 Introduction

In chapter four, four types of eclogite were identified based upon different mineralogies seen both in the field and in thin section, namely: bimineralic eclogite; orthopyroxene - bearing eclogite; quartz eclogite; and a single biotite - rich eclogite. All four contain similar textures and appear to have undergone a similar history. The first three types contain streaks of quartz - feldspar - kyanite (QFK) that are interpreted to represent intruded veins, whilst amphibole - biotite - feldspar occur in the first and last types and appears to be of similar age to the QFK streaks. The retrogression of these eclogites was described, both in association with veins resulting from brittle deformation and as alteration of the entire rock associated with ductile deformation.

In this chapter the bulk chemistry and mineralogy of the four eclogite types and of their retrogressive products are described. Major and minor element whole rock analyses were obtained by XRF. Major element mineral analyses were obtained using an electron probe and trace element analyses using an ion probe. Fe''' content of garnets and pyroxenes were calculated after Droop (1987). Calculation after Ryburn *et al.* (1976) gave similar figures for Fe''' content. Fe''' content of amphiboles was estimated using the methods described by Robinson *et al.* (1982). Analytical procedures are described in appendix II. Representative whole rock analyses and mineral analyses are given in appendix III and IV respectively. All plots of mineral analyses for any one group of eclogites contain more than one analysis from each sample analysed, often with more than one analysis from any one grain. For major element analyses, 11 samples were used for the bimineralic eclogite, 8 for the quartz - eclogite, 11 for the orthopyroxene eclogite, 4 for the coarse garnet (2 with clinopyroxene) and 1 for the biotite eclogite.

5.2 Bulk chemistry

Alderman (1936) and Yoder and Tilley (1962) demonstrated that the bulk of the eclogites from the Eastern Lewisian of Glenelg were iron rich basic rocks with abundant normative hypersthene and either olivine or quartz. Mercy and O'Hara (1968) described a Na_2O rich nepheline - normative rock from alongside Loch Duich.

Although only a small number of samples were analysed by XRF, it appears that the different eclogite types have distinct normative characteristics. The bimineralic eclogite, not described by Alderman (1936) or Yoder and Tilley (1962), is a nepheline - normative alkali basalt. The biotite - eclogite is corundum - normative. The quartz - eclogite is quartz - normative and the orthopyroxene - eclogite, olivine - normative. The areas of coarse garnet with or without clinopyroxene within the bimineralic eclogites (described in chapter three) represent aluminous rich regions.

The question as to whether quartz eclogites are related to, and derived from, QFK streaks is not readily answered by XRF analysis. Rocks bearing QFK streaks would be expected to be Na, K, Al, Si, (Ca) rich compared to their QFK streak - free counterparts. Thus SN. 96 is a bimineralic eclogite with up to 50% QFK streaks, and the whole rock composition is Na, K, Al, Si rich (and Ba, Sr rich) compared to the QFK streak - free bimineralic eclogites (see appendix III). SN. 223 is an orthopyroxene eclogite with up to 50% QFK streaks with a whole rock composition rich in K, Na, Al and Si relative to the orthopyroxene eclogite of O'Hara (1960) (appendix III). However, the QFK streak - free equivalents of rocks are not always either sampled or even exist, thus SN. 223 is not enriched in Na, K or Si compared to the two - pyroxene rock, SN. 511. There are also differences within the bimineralic eclogite. SN. E2, with primary amphibole, biotite and plagioclase, is the most K, Al rich of the rocks from Lochan Na Beinne Faide, but it is impossible to tell from XRF analyses whether the rock was originally K, Al rich, and therefore more likely than other eclogite to contain biotite, or whether this is a result of injection of some K, Al (in particular) rich fluid, causing the growth of primary biotite. Trying to establish whether the quartz - eclogites form from intrusion of large quantities of QFK material or not is fraught with difficulty because if they are, then the rocks may well be Na, K, Al, Si rich compared to some unknown precursor composition, which cannot be proved on the basis of available chemical data because no K, Na, Al, Si poor equivalents of quartz eclogites have been found.

Most amphibolites within the Eastern Lewisian appear to be either quartz - or olivine - normative, with compositions similar to the eclogites, although very few samples were analysed. By comparing eclogites with retrogressed eclogite or amphibolite from the same locality, e.g. SN's. 83 & 82; SN's. E5 & E1, there appears to be little change in bulk rock composition with retrogression, merely a change in mineralogy.

5.3 Mineral chemistry

5.3.1 Garnet

Along with jadeite - rich pyroxene, garnet is the ubiquitous eclogite facies mineral. Garnet from fresh bimineralic eclogites are fairly Mg rich, with up to 35% pyrope ($Mg_3Al_2Si_3O_{12}$) and 25% grossular ($Ca_3Al_2Si_3O_{12}$) and other Ca - end members. Garnets from orthopyroxene - bearing eclogite tend to be more pyrope rich, often with 45 - 50% pyrope and only 15 - 20% Ca - garnet. Garnets from quartz - eclogites are usually more grossular rich, with up to 40% Ca - garnet, and only 25 - 30% pyrope. These variations were noted by Sanders (1972), who suggested that they were related to changes in bulk composition, thus, for instance, Mg - rich rocks produced orthopyroxene - eclogites with Mg - rich garnets. Garnets from the biotite - rich eclogite are significantly Ca - poor, with very little grossular, but 6% andradite ($Ca_3Fe'''_2Si_3O_{12}$) and about 30 - 35% pyrope. The coarse garnets within the bimineralic eclogites are also Ca - poor, with about 20% grossular. Mn content is low in all cases with usually only 0 - 2% spessartine ($Mn_3Al_2Si_3O_{12}$). The compositions of garnet cores from all eclogite types are summarised in figure 5.1 where they are compared to the compositional fields for eclogite garnets of Mottana (1986) and Coleman *et al.* (1965). Garnets from the orthopyroxene eclogite are the most Mg - rich, those from the quartz eclogite the most Fe - rich. Bimineralic eclogite garnets lie in between, as described by Sanders (1972).

Traverses were made across garnets from representative samples of each of the eclogite types. These are plotted in figures 5.2 - 5.5, for bimineralic eclogite, orthopyroxene - eclogite and quartz - eclogite and QFK streaks respectively. Garnets from bimineralic and orthopyroxene eclogites tend to have homogenous core compositions, with alteration at grain rims and alongside cracks to more FeO - rich, MgO - poor compositions. Quartz eclogites tend to be CaO - rich, but with similar changes to FeO - rich, MgO - poor compositions at grain rims and alongside cracks. SN. 83 (figure 5.4) is distinctive and apparently contains three sets of compositions, each more CaO - rich out from the core. Three of the four garnets from QFK streaks, including an orthopyroxene eclogite (SN. 218), show enrichment of CaO at grain rims, although each appears to have an homogenous, CaO - poor, core. SN. 223, also an orthopyroxene eclogite, has a fairly flat profile with little or no enrichment of CaO at the grain rim.

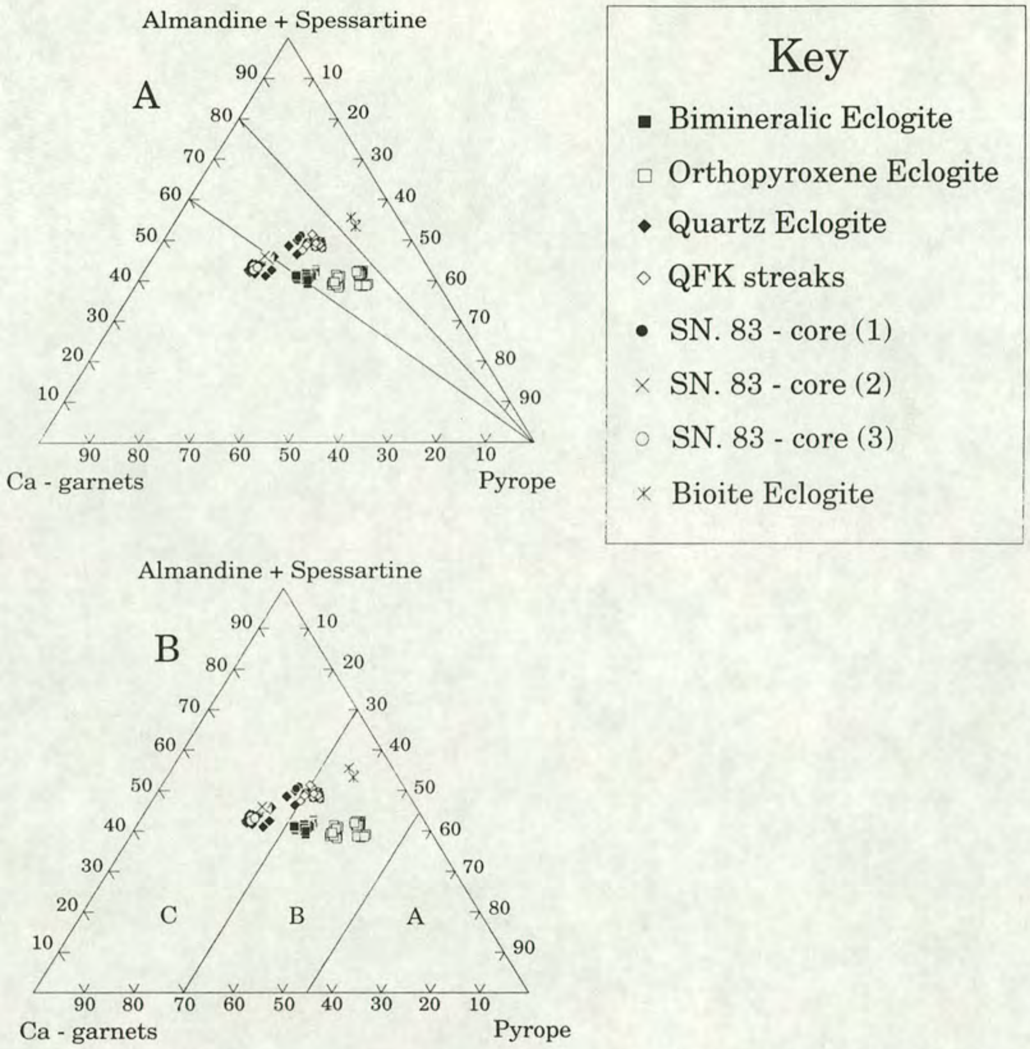


Figure 5.1 End member plots for cores of garnet from all Eastern Lewisian eclogite types. Garnets from orthopyroxene eclogites are the most Mg rich, those from quartz eclogites the most Mg poor. Garnets from the biotite eclogite are Ca poor. Those from bimineralic eclogites fall between these other compositions. **A :** compositional field of eclogite garnets after Mottana (1986). Garnets from the biotite eclogite are Ca poor and fall outside the eclogite field, whilst many of those from quartz eclogites are Ca rich. The three compositions from SN. 83 correspond to the three plateau seen in the profile (figure 5.4). **B :** compositional fields of eclogite garnets after Coleman *et al.* (1965). The eclogites plot as B and C type eclogites, interpreted by Coleman *et al.* as being regionally metamorphosed and blueschist - related eclogites respectively.

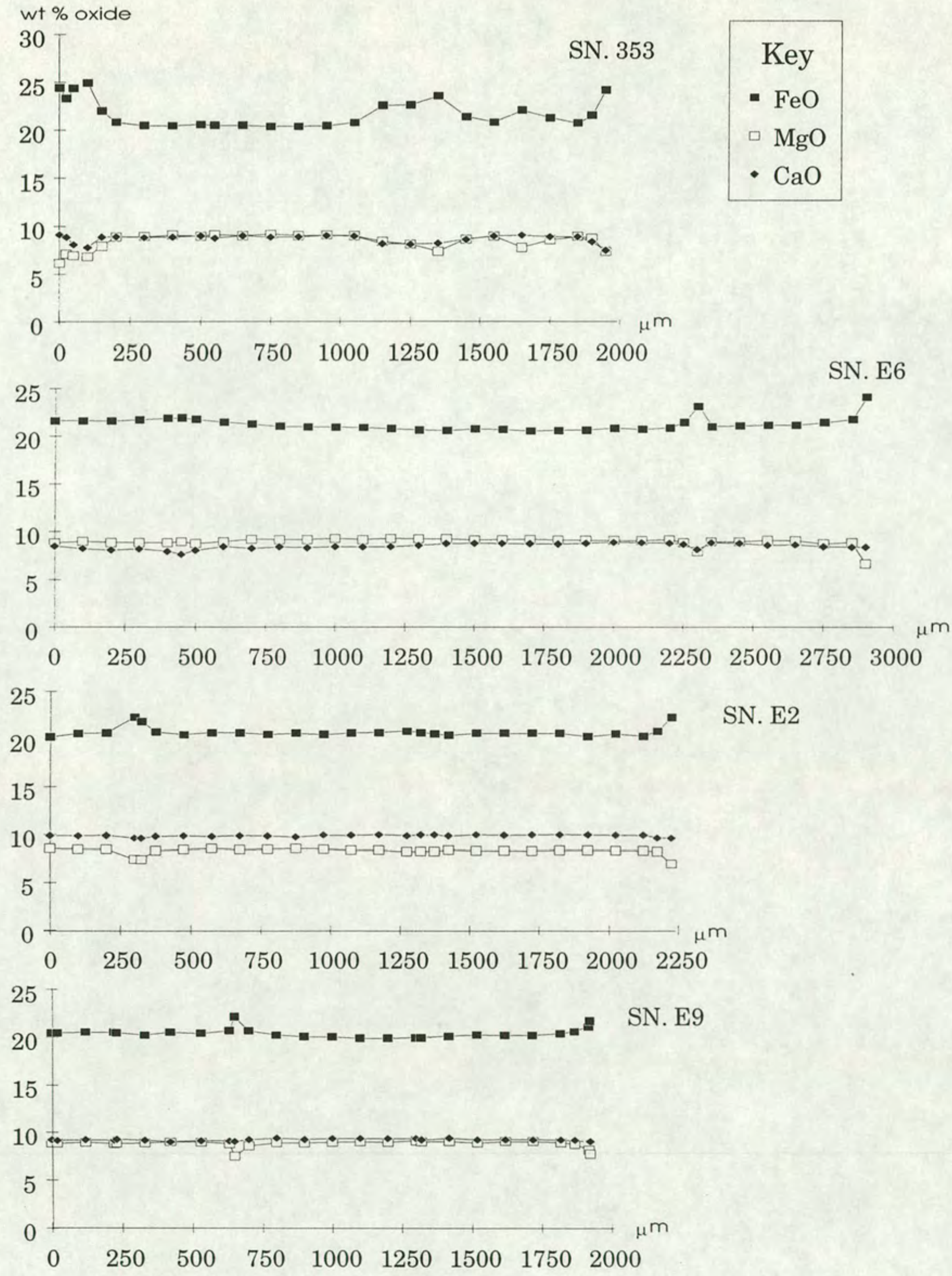


Figure 5.2 Profiles across garnets from four bimineralic eclogites. SN. 353 is from rim to rim, others from core (left) to rim (right). All show flat profiles apart from a gain in FeO and corresponding loss of MgO within 100 - 150 μm of grain rims and alongside cracks. The slightly FeO rich part of SN. E6 at the left of the profile contains many small clinopyroxene inclusions. MnO contents are low in all cases (< 2 wt % MnO) and are not plotted.

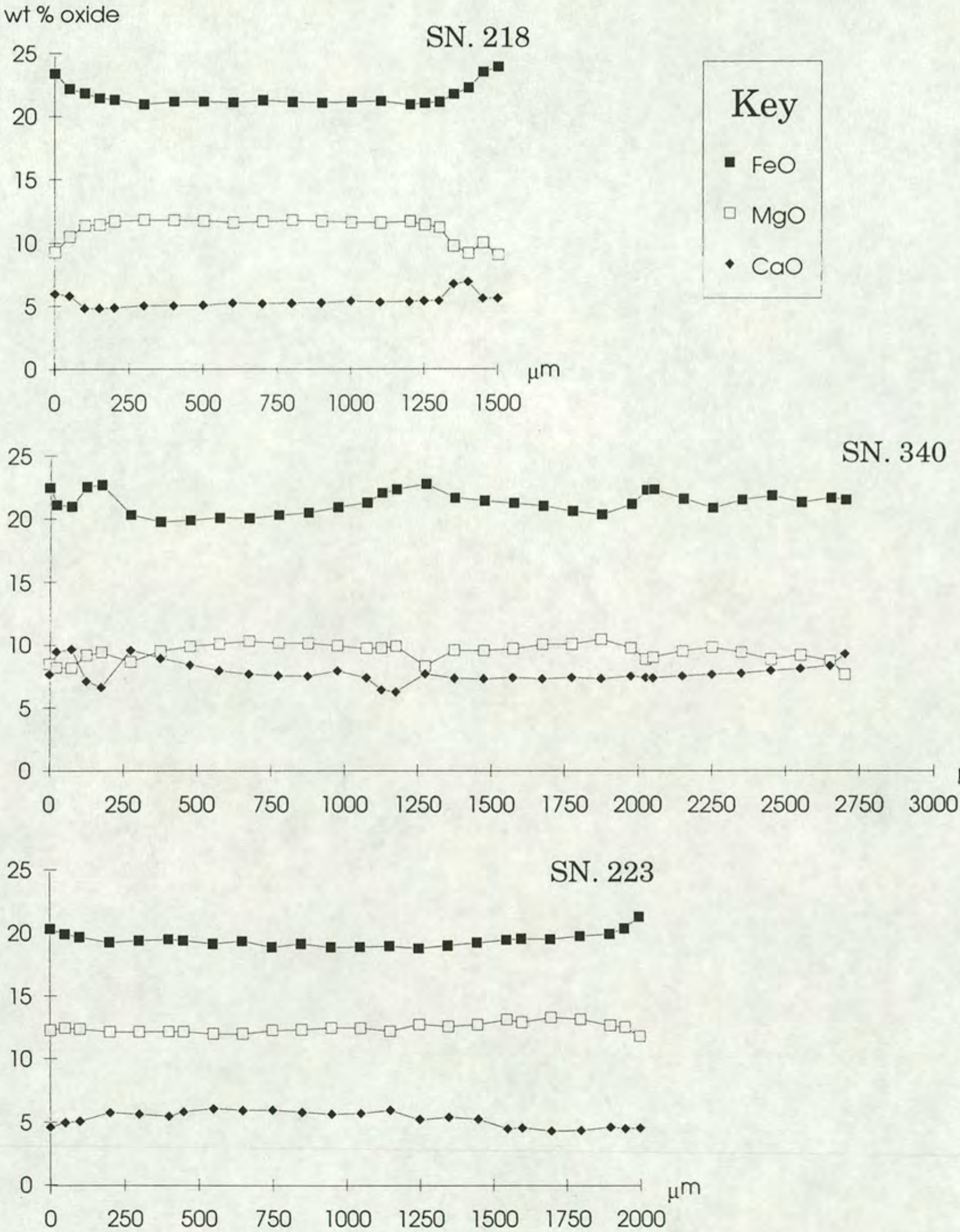


Figure 5.3 Profiles across garnets from three orthopyroxene bearing eclogites. All three are from rim to rim, showing fairly flat profiles, with FeO poor cores and rich rims, although these proifles are in general more rounded than for the bimineralic eclogite. SN. 340 in particular shows changes in FeO and MgO close to veins across garnets, although to the left of the profile there is are two points rich in FeO and MgO and correspondingly poor in CaO, which are from a region of the garnet containing small quartz inclusions. MnO contents are low in all cases (< 2 wt % MnO) and are not plotted.

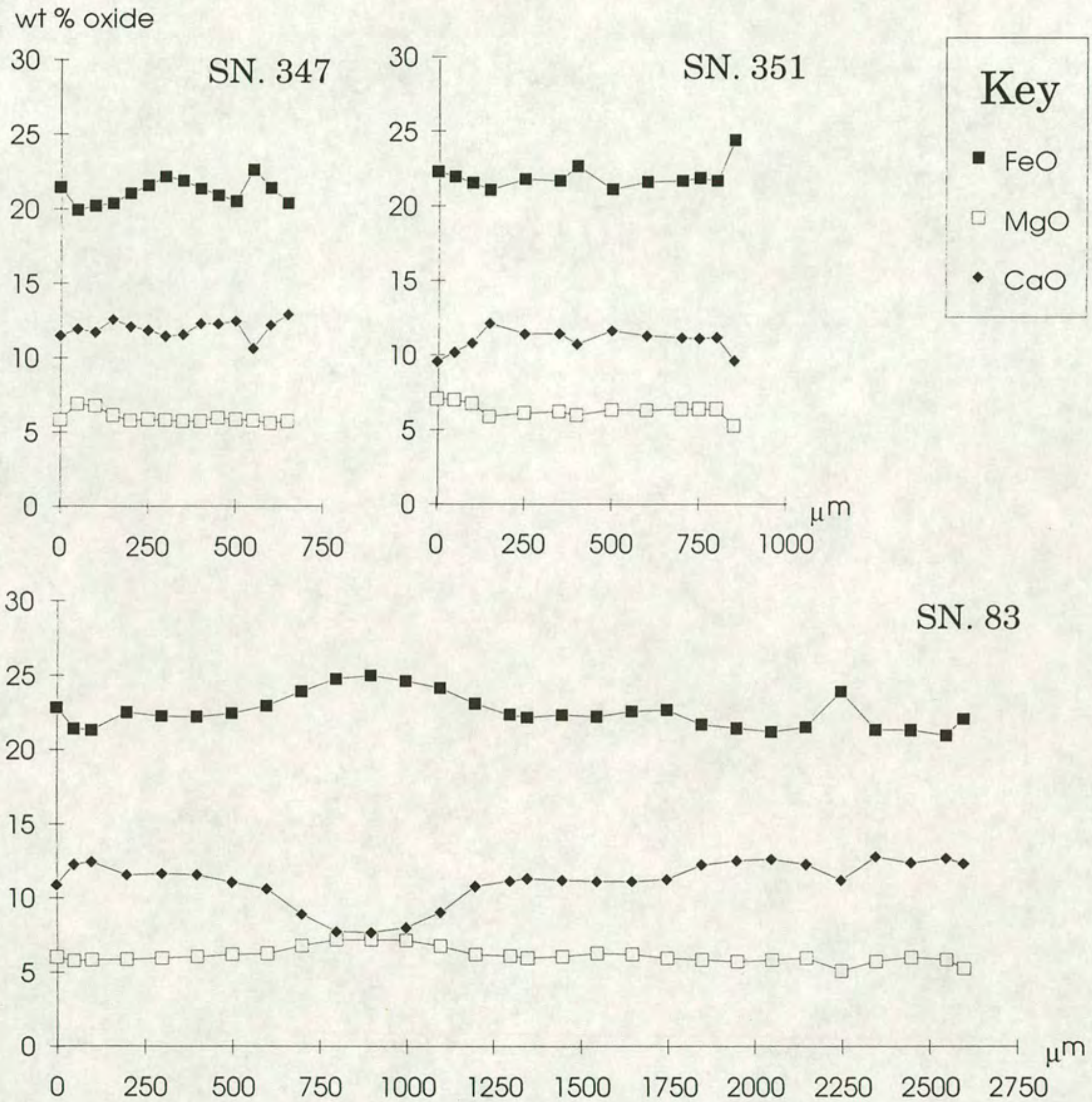


Figure 5.4 Profiles across garnets from three quartz eclogites. All three from rim to rim. SN.'s 347 & 351 show flatish profiles with enrichment in FeO and loss of CaO at vein edges and grain rims. SN. 83 shows similar features but also appears to have three distinct compositions, each CaO richer and FeO poorer out from the grain core. A line of tiny sphene and quartz inclusions occurs at ≈ 2000 μm. MnO contents are low in all cases (< 2 wt % MnO) and are not plotted.

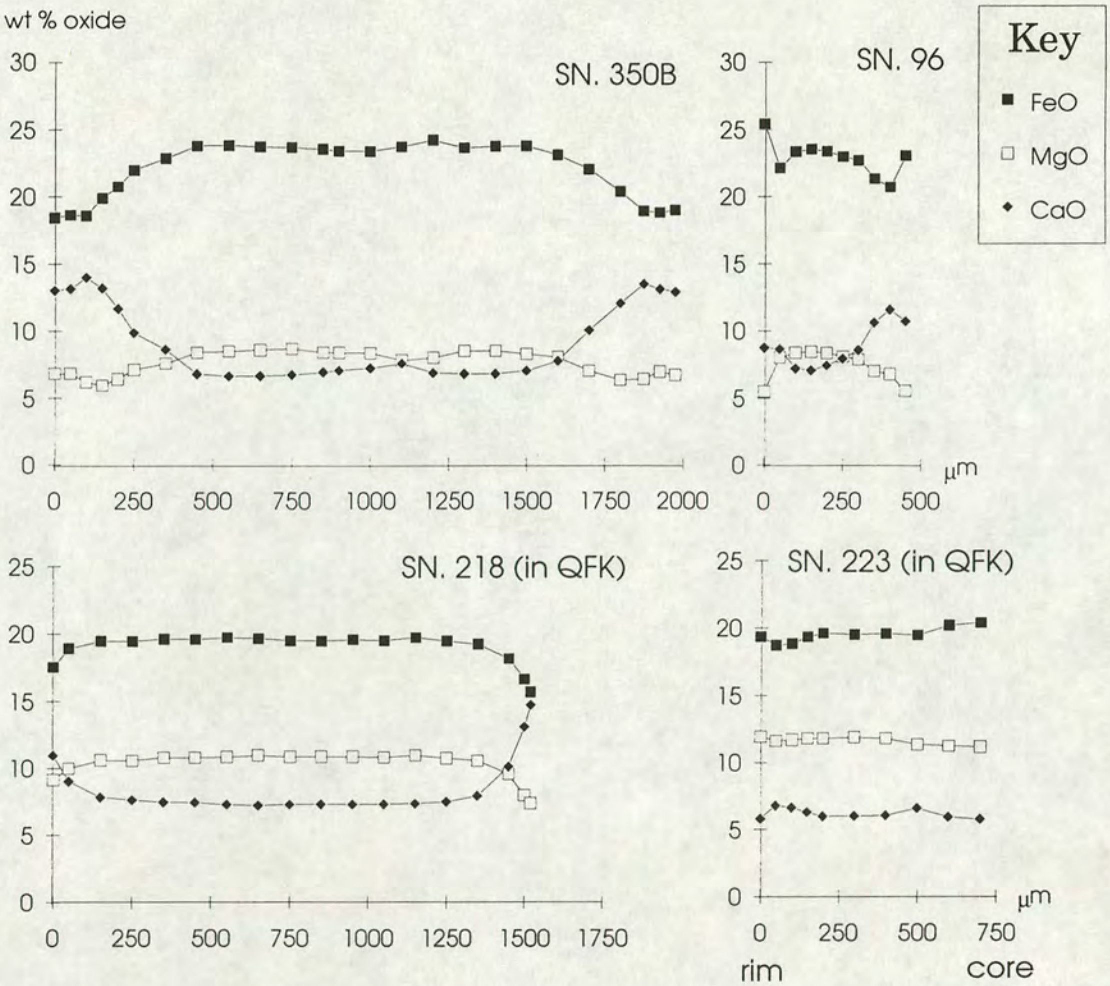


Figure 5.5 Profiles across four garnets within QFK streaks. All but SN. 223 are from rim to rim, SN. 223 is from rim (left) to core (right). All the larger grains show flat cores, with a large increase in CaO at grain rims and a corresponding drop in FeO and MgO. Sanders (1988) suggests that this is due to breakdown of anorthite within QFK streaks to form grossular at high pressure. SN. 96 shows a general increase in CaO towards grain rims and also an increase in FeO and corresponding drop in MgO at the grain rim, similar to garnets from other eclogite types. SN. 223 shows little increase in CaO at grain rims. MnO contents are low in all cases (< 2 wt % MnO) and are not plotted.

Variations in garnet composition from the core compositions outlined above occur along two principal trends, one a change in Ca content, the other a change in Mg no. Both changes are apparent to a greater or lesser extent in each of the main eclogite types.

Figure 5.6 shows end member garnet compositions from representative bimineralic eclogites. Within bimineralic eclogite garnets it has already been demonstrated (figure 5.2) that Fe and Mg content varies at grain rims and alongside cracks, often filled by secondary amphibole. However, there are also variations in Ca content, possibly related to primary, brown, amphibole occurrence. SN.'s E1, E2, E6 and E9, plotted on figure 5.6, are all from the same locality close to Lochan na Beinn Faide (chapter three), but have differing proportions of brown amphibole, E1 and E6 have very little; E9 has some; and E2 a large proportion (chapter four). Figure 5.6 demonstrates a corresponding increase in Ca - content of the garnets. Garnets from SN. 353, from Loch Coire an Daimh (chapter three), show a change in Fe and Mg contents at grain rims, figure 5.7, but cores of garnets show no real change in composition whether they are inclusion - free garnets with clinopyroxene, garnet - quartz aggregates, or garnets within quartz streaks.

Orthopyroxene eclogite garnets have a wide range of compositions, increasing in both Fe and Ca from core compositions. Garnets from representative samples are plotted in figure 5.8. Garnets from SN. 512 are the most Mg rich, but these are secondary (chapter four). Garnets from SN. 223 are also Mg rich. Generally these have fairly constant Ca content, even at the rims of QFK streaks. As in SN. 353, the occurrence of garnet - quartz aggregate seems to make no difference to garnet compositions in either of the above samples. SN.'s 338, 340 and 218 are from the same outcrop. In SN. 218 garnet within a QFK streak is Ca richer than that in body of rock, with extremely Ca rich rims. As with samples E1, E2, E6 and E9, there is a wide range of compositions occurring within samples from a single locality.

Quartz eclogites show a wide range of compositions, from rare Ca - poor cores (figure 5.1) to predominantly Ca rich compositions compared to garnets from other eclogite types. Representative samples are shown in figure 5.9 (SN.'s 83, 347, 351). SN.'s 347 and 351 have only Ca rich compositions, with some Fe - rich, Mg poor compositions from alongside cracks and at grain rims. Rare garnets from SN. 83 have Ca - poor cores, but most, whether as large or small garnets within the bulk of the rock, are of similar compositions to garnets from other quartz eclogites.

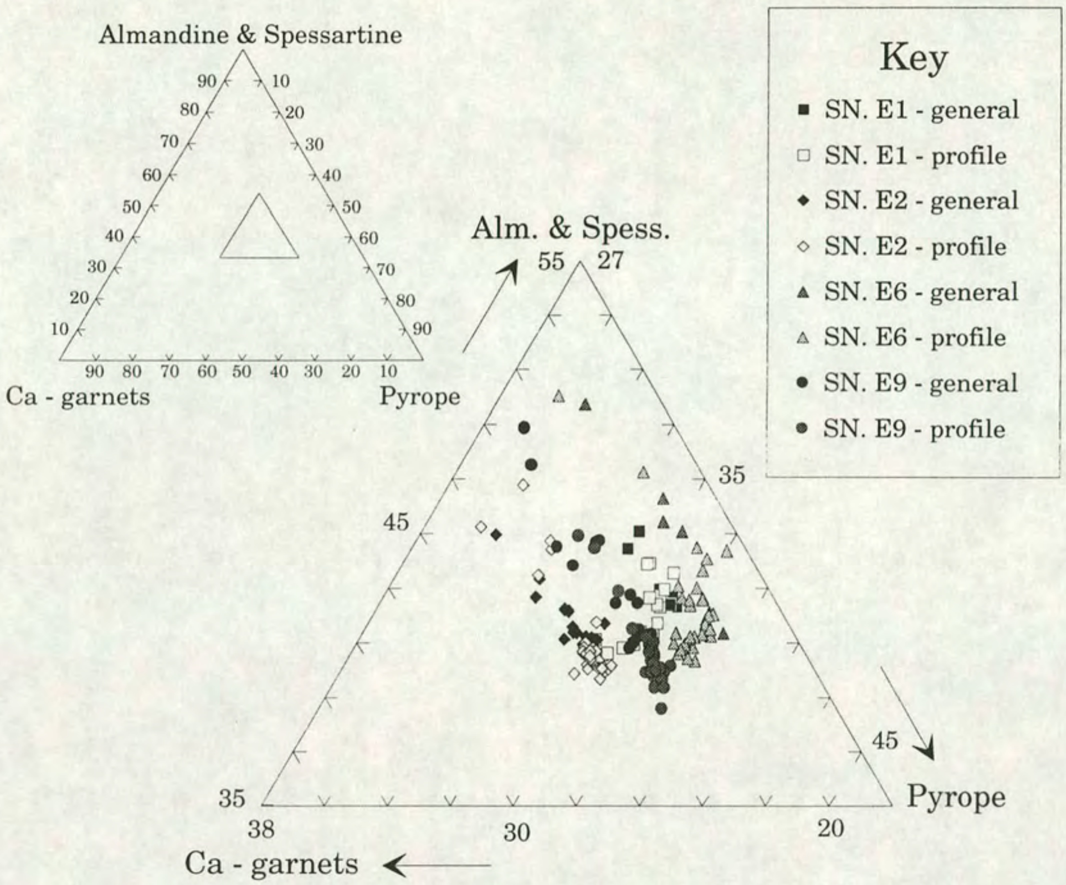


Figure 5.6 End member plot for garnets from bimineralic eclogites. The small triangle shows the position of the main triangle. The garnets show a range of compositions, with up to 39 % pyrope, but with some Fe rich compositions, as noted in Figure 5.2 for garnet profiles. However, each sample, all collected from within twenty metres of each other at one locality, close to Lochan na Beinn Faide (chapter 3), has a slightly different Ca content. SN. E2 shows the highest and contains primary brown amphibole as well as biotite and plagioclase. SN. E6 has the lowest Ca content and has little amphibole etc. However, both SN.'s E1 & E6 show an increase in Ca content with respect to Fe content, corresponding to their most Mg rich compositions. Other bimineralic eclogite garnets both from the same and other localities have similar compositions to those plotted above.

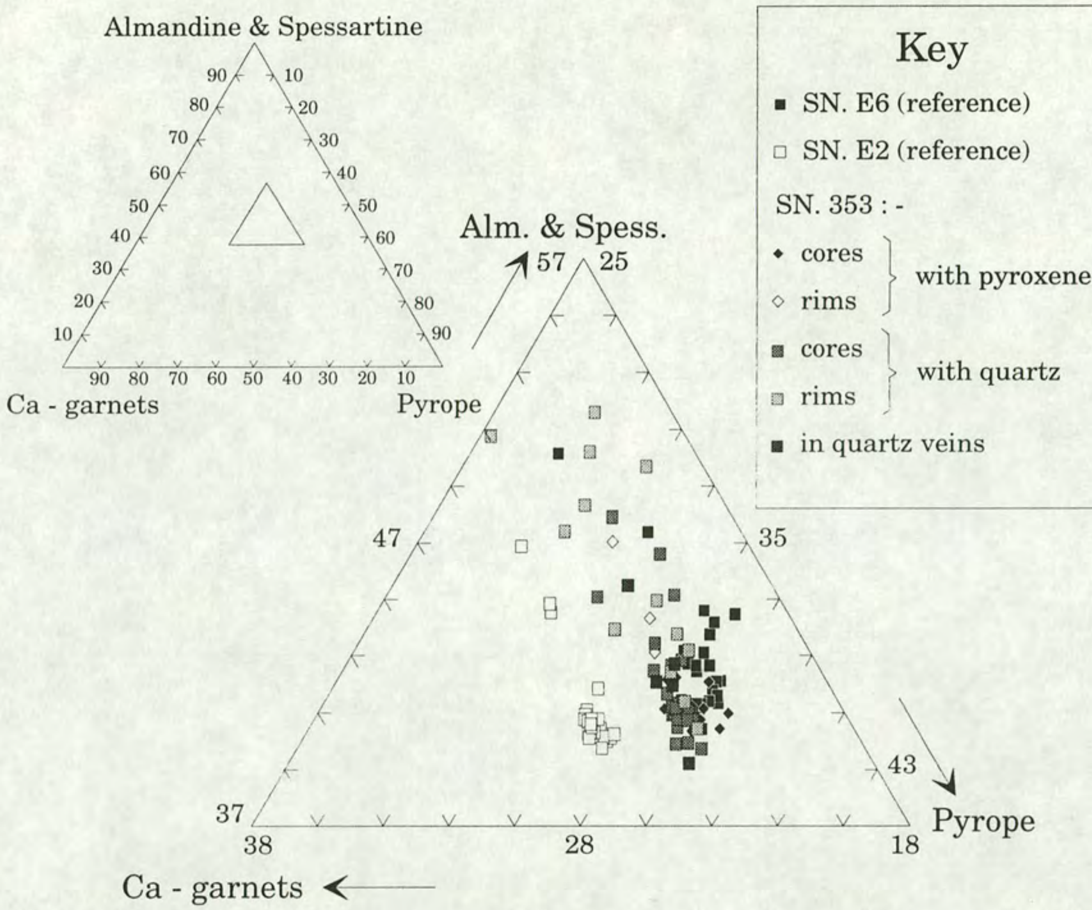


Figure 5.7 End member plot for garnets from SN. 353. The small triangle shows the location of the large triangle. SN. 353, a bimineralic eclogite from near to Loch Coire an Daimh (chapter 3) contains regions with garnet - quartz aggregate that pass into quartz veins with garnet inclusions. There is also some primary brown amphibole and biotite (chapter 4). There is a general change in FeO and MgO ratios at grain rims and alongside cracks, shown in profile for one garnet in figure 5.2. However, garnets within bimineralic portions of the sample and associated with quartz aggregates and quartz veins all have similar compositions. Note that SN.'s E2 and E6 are represented by different symbols to those in figure 5.6.

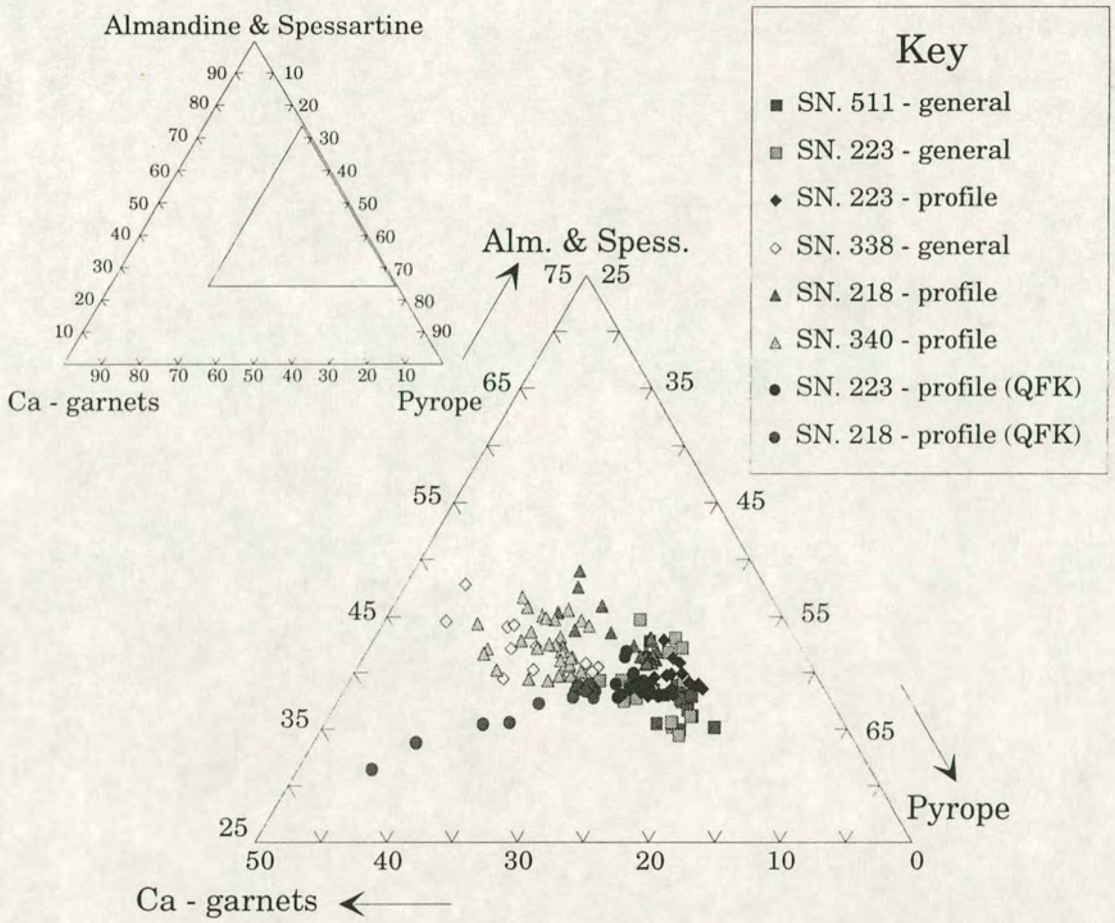


Figure 5.8 End member plot for garnets from orthopyroxene eclogites with and without QFK streaks. The small triangle shows the location of the large triangle. Note change of scale from figures 5.6 & 7. Orthopyroxene eclogite garnets are Mg rich. Those from SN. 512, a two pyroxene rock with only secondary garnet, are the most Mg rich, along with those from SN. 223. In general the compositions range from Mg rich cores to comparatively Fe & Ca rich rims. SN.'s 223 & 218 contain QFK streaks, and garnets from both of these are Ca rich compared to samples from within the mafic portion of the sample (compare figures 5.3 and 5.5). Garnet from the streak within SN. 218 in particular shows a large increase in Ca content at grain rims.

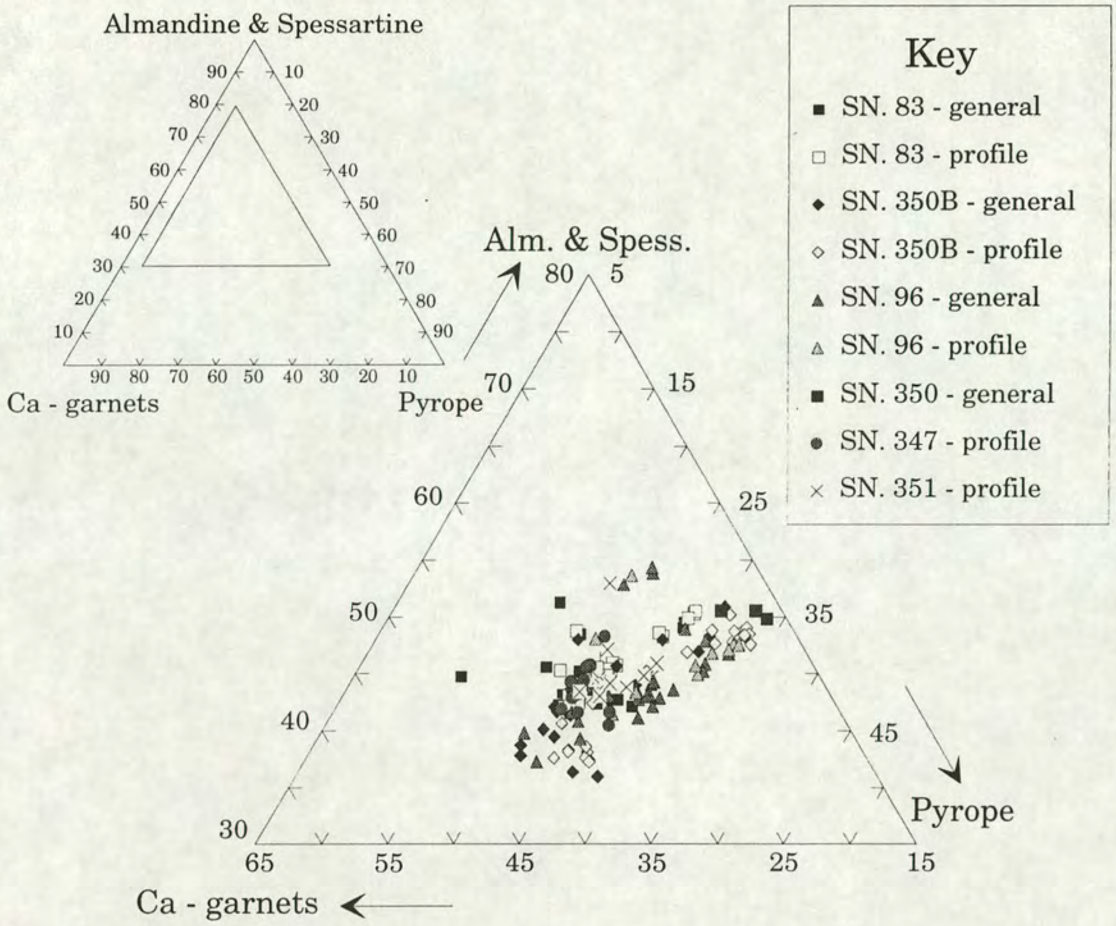


Figure 5.9 End member plot for garnets from quartz eclogites and QFK streaks across bimineralic eclogite. The small triangle shows the location of main the triangle. Garnets from both quartz eclogites and QFK streaks are Fe and Ca richer than other garnets (see figure 5.1). Rare samples of quartz eclogite (e.g. SN. 83) and more common QFK streak garnets show Ca poor cores, with lower Ca content than many other eclogite types (see also figure 5.1). However, many quartz eclogites show only Ca rich compositions, similar in composition to the rims of garnets from QFK streaks, although generally Mg poor. There are also rare Fe rich, Mg poor compositions, relating to changes at grain edges and vein rims similar to other eclogite types.

Garnets from QFK streaks are also plotted on figure 5.9. They show a similar range of compositions as the quartz eclogites, from Ca - poor to Ca - rich compositions, but in general they are richer in Mg. Figure 5.10 plots garnets from SN. 83 and shows that garnets from within QFK patches in the quartz eclogite are also Mg rich. As noted above, QFK streaks occur within orthopyroxene eclogite. In SN. 218 Ca content increases towards the garnet rim, producing garnet of similar composition to the most Ca rich QFK streak garnets. In SN. 223 there is no increase in Ca content at vein rims.

Trace element compositions of garnets from a number of bimineralic eclogites show slight enrichment in HREE's (figure 5.11.A), with no Eu anomaly, although garnet rims have slightly lower contents than cores. Garnets from eclogites bearing QFK streaks show anomalous trace element contents. SN.'s 83 and 217 are characteristic of this. Away from QFK streaks garnets in both show trace element compositions similar to those rocks without QFK streaks (figure 5.11.B), although in SN. 83, a quartz eclogite with rounded QFK patches, some garnet away from QFK streaks is more enriched in HREE's than those in bimineralic eclogites. In both samples, garnet occurring within the streaks shows significant reduction in HREE content compared to both bimineralic eclogite garnets and eclogites outwith the QFK streaks.

Garnets within garnet - amphibolite from retrogressed eclogite are generally Fe - rich, Mg - poor compared to those of the eclogites, but are often of similar composition to the rims of eclogite garnets. However, the wide range of garnet composition within the eclogites is reflected in the composition of garnets from retrogressed rocks, with those from retrogressed quartz - eclogite being generally Ca - rich and those from retrogressed bimineralic eclogite Ca - poor. Garnets from mylonitised eclogite also show a range of compositions, generally similar to those at the rims of garnets within unaltered eclogite, rather than the cores.

Profiles of garnets from a garnet amphibolite (SN. 84) and from a mylonitised eclogite (SN. Du4) are plotted in figure 5.12. Both show fairly homogenous cores. SN. 84 is derived from a quartz eclogite and the Ca - rich rim is almost certainly inherited.

5.3.2 Summary of garnet compositions

The compositions of garnets from different eclogite types reflect the bulk compositions of the rocks, with orthopyroxene eclogite garnets being the most Mg - rich, and quartz - eclogites the most Mg - poor. Garnets from bimineralic eclogite,

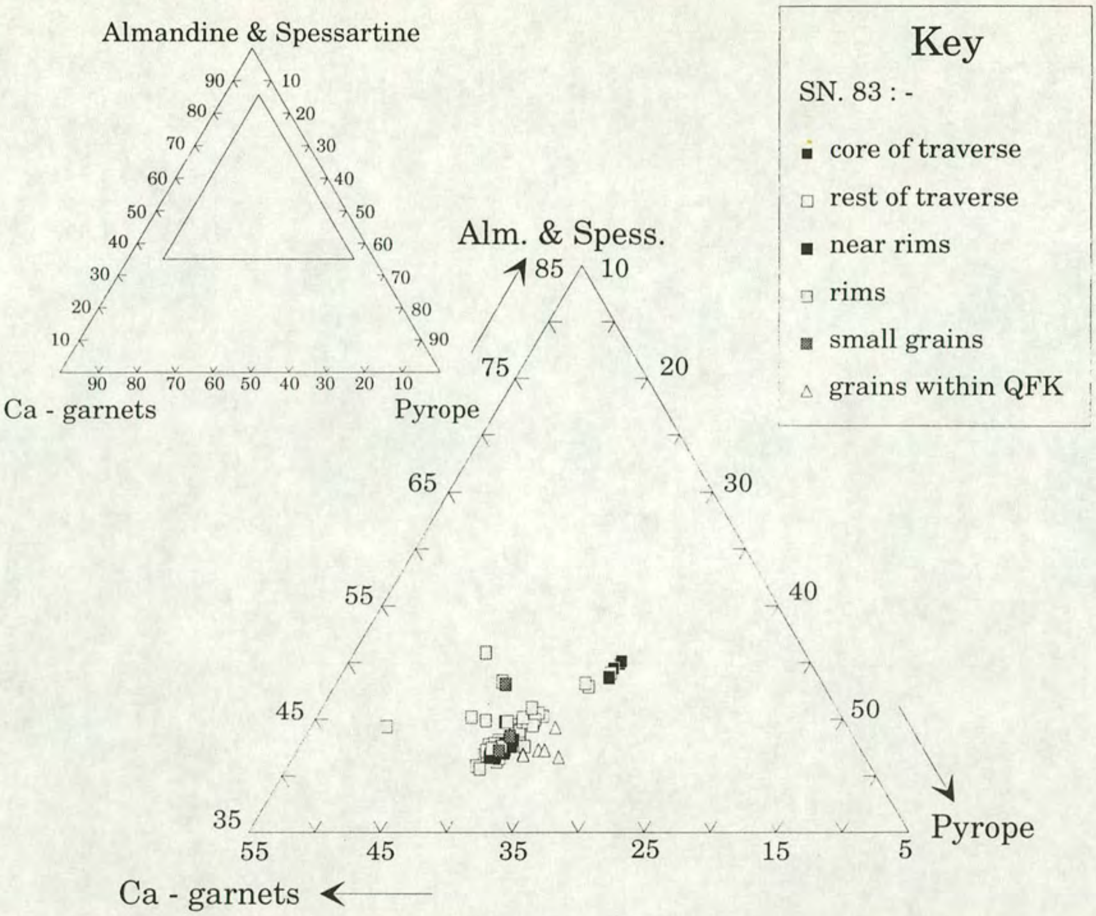


Figure 5.10 End member plot for garnets from SN. 83. The small triangle shows the location of main the triangle. SN. 83, a quartz eclogite, shows rare garnet with Ca poor cores. Otherwise most garnets, whether large or small within the bulk of the rock, have similar compositions, being Ca & Fe rich compared to other eclogite types. However, garnets from within QFK patches are Mg richer than others.

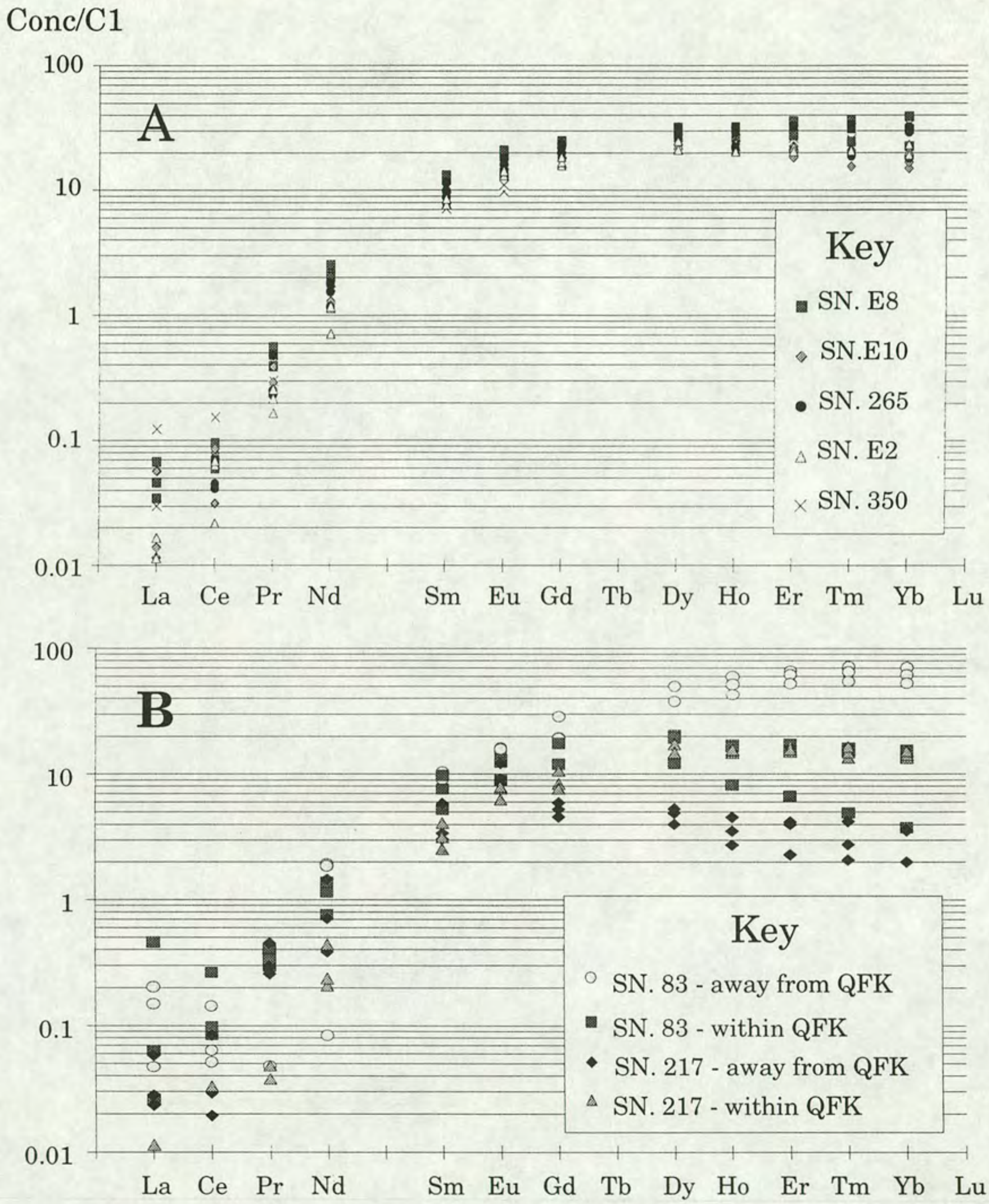


Figure 5.11 REE compositions of eclogite garnets, normalised to C1 chondrite compositions. A : Garnets from most eclogites show typical REE traces, with enrichment in HREE's. **B :** Garnets from SN. 83, a quartz eclogite, and SN. 217, both with QFK patches or streaks, show different features. Both contain garnets with REE compositions similar to those from other rocks within the bulk of the rock, although those in SN. 83 are actually HREE richer. However, garnets from QFK areas within the samples are HREE depleted. Note that there is no Eu anomaly.

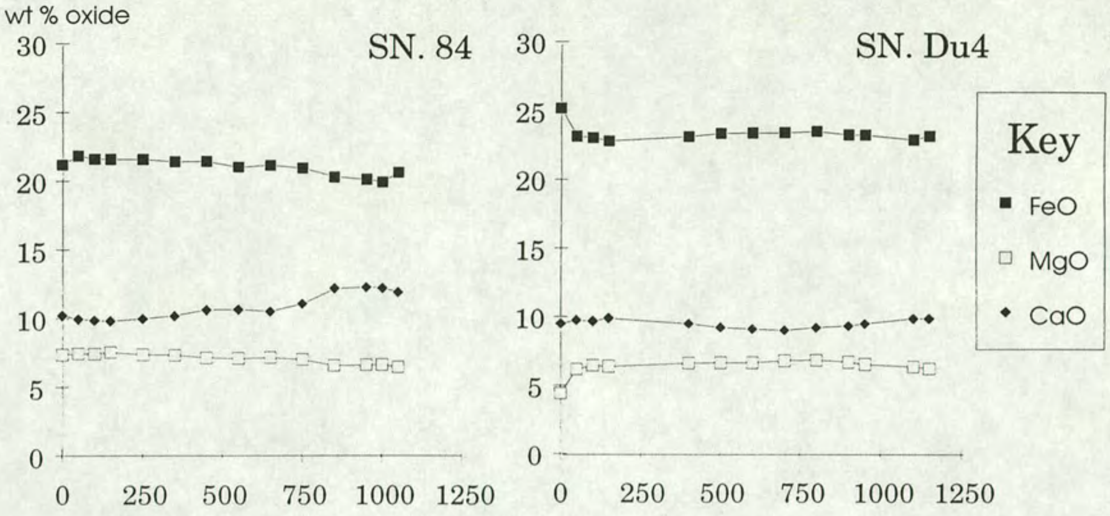


Figure 5.12 Profiles across garnets from garnet amphibolite (SN. 84) and mylonitised eclogite (SN. Du4). Both garnets show reasonably flat profiles similar to those in eclogite proper, although the garnet amphibolite show some enrichment in CaO at grain rims. This sample is derived from a quartz eclogite and the garnets are relicts of the eclogite facies metamorphism, thus an increase in CaO is probably a relict feature. The sharp gain in FeO and loss of MgO at the margins of the garnet from a mylonitised eclogite are similar features to many of the eclogite types.

orthopyroxene eclogite and QFK streaks all show flat homogenous cores. Profiles of garnets from all but one of the quartz eclogites were generally too small to show whether flat cores existed or not. The only profile across a coarse garnet, in SN. 83, showed three separate 'core' compositions.

In general there are six important points :

a) Coarse anhedral garnet and polygonal garnet show little difference in composition, implying that they formed at similar temperatures of metamorphism.

b) Garnets within QFK streaks and at streak rims are generally Ca rich, suggested by Sanders (1988) to be due to the breakdown of anorthite. In some samples, e.g. SN. 223, they are not. This is thought to imply that there was little anorthite within some of the QFK streaks.

c) The garnets from SN. 83 (a quartz eclogite) are odd. They have apparently euhedral cores with anhedral overgrowths, the opposite to all other eclogites. Compositional differences within crystals occur mostly within the euhedral cores, rather than between core and overgrowth.

d) All quartz eclogites apparently show Ca - rich garnets with only rare Ca - poor compositions, but all quartz eclogite garnets plot on a trend of increasing Ca - content and fairly constant Mg no. They are similar in composition to those from QFK streaks which show a similar trend.

e) The increase in the amount of brown amphibole within bimineralic eclogites from Lochan na Beinn Faide appears to be related to an increase in Ca - content of the garnets.

f) Garnets within the streaks appear to be HREE poor, and have a peak at Eu. This could well be because the garnets within the QFK streaks have grown due to the breakdown of anorthite, as suggested by Sanders (1988), and have inherited the HREE poor compositions of the original anorthite.

Garnets within eclogites containing primary brown amphibole, within some quartz - eclogite (the second type outlined in chapter three), and within QFK streaks are all Ca rich compared to other garnets, either within other bimineralic eclogites or outwith

QFK streaks. It is therefore possible that the occurrence of quartz eclogite and the presence of brown primary amphibole are related to the presence of QFK streaks.

5.3.3 Clinopyroxene

Clinopyroxene from fresh eclogite is usually omphacitic (pyroxene with jadeite content higher than 10%). White (1960) defines clinopyroxenes from metabasic eclogites as having a jadeite : tschermakite ratio of > 0.4. The jadeite content of clinopyroxene is important as it gives an indication of the pressure of formation (Holland, 1980, 1983). Clinopyroxene has a general formula XYZ_2O_6, in which X is (Na,Ca,Mg); Y is (Mg,Fe'',Mn,Al,Fe'''), in six - fold co - ordination; and Z is (Al,Si), in four - fold co - ordination. In general Na(Al,Fe''') substitutes for Ca(Mg,Fe'') to form jadeite ($NaAlSi_2O_6$) and aegerine ($NaFe'''Si_2O_6$). $(Al,Fe''')_{iv}$ combines with Al_{vi} to form pyroxene with tschermak's molecule, $(Ca,Mg)(Al,Fe''',Ti)_2SiO_6$. Because Al and Fe''' in the Y (vi) site can both form end - members with either Na or Al_{iv}, the actual proportions of jadeite and aegerine cannot be accurately obtained because the proportions of Al and Fe''' in Y site of the tschermak's aren't known. If jadeite content is calculated first (Cawthorn and Collerson, 1974) with all available Al_{vi} combining with available Na, a maximum jadeite content is obtained, which will almost certainly be an overestimate. If aegerine is calculated first (Yoder and Tilley, 1962), then the remaining Na combines with Al_{vi}, to give jadeite, which will give a minimum estimate of jadeite content. Figure 5.13 plots Na vs Al_{vi} for Eastern Lewisian eclogite clinopyroxenes, and shows that Na content approximately equals Al_{vi} content, and thus the method of Cawthorn and Collerson is used to calculate jadeite contents and most Fe''' is in the tschermak's molecule. However, plots of end member compositions have not been used to avoid possible difficulties with assigning Fe''' and Al, thus Al_{vi} and Fe''' are plotted against Mg + Fe'' + Mn, which roughly equates to jadeite, tschermak's and diopside & hedenbergite. Table 5.1 (over page) shows the effects of calculating either jadeite, aegerine or tschermak's molecule first, for two different pyroxenes, one Fe''' poor with Na < Al_{vi}, the other Fe''' rich with Na > Al_{vi}. When Na < Al_{vi}, the jadeite content can be estimated fairly accurately. When Na > Al_{vi} the proportions of the end members relies heavily on which end member is calculated first and on how much Fe''' is apportioned to tschermak's molecule. In this case jadeite content cannot be estimated accurately. The actual (as opposed to calculated) Fe'' contents and jadeite contents have important implications for thermobarometry and thus pressure and temperature estimates for many rocks with a high estimated Fe''' content are open to large inaccuracies. This is discussed further in chapter ten and appendix VI.

Table 5.1

	E2/3				353/1			
SiO2	54.063				53.794			
TiO2	0.269				0.258			
Al2O3	10.274				8.674			
Cr2O3	0.021				0.072			
FeO	4.064				4.828			
MnO	0.054				0.041			
MgO	9.573				10.268			
CaO	16.217				16.871			
Na2O	5.016				4.863			
K2O	0.009				0.005			
Total	**99.56**				**99.674**			
Si	1.944	**jd. first**	Jadeite	**34.98**	1.936	**jd. first**	Jadeite	**30.38**
Al(iv)	0.056		Aegerine	**0.00**	0.064		Aegerine	**3.55**
Al(vi)	0.380		Tsch.	**5.20**	0.304		Tsch.	**5.99**
Ti	0.007		Heden.	**11.32**	0.007		Heden.	**6.25**
Fe'''	0.011		Diopside	**48.50**	0.084		Diopside	**53.83**
Cr	0.001				0.002			
Fe''	0.112	**tsch. first**	Jadeite	**33.50**	0.061	**tsch. first**	Jadeite	**30.38**
Mn	0.002	**(Fe''' in tsch)**	Aegerine	**0.00**	0.001	**(Fe''' in tsch)**	Aegerine	**2.17**
Mg	0.513		Tsch.	**5.57**	0.551		Tsch.	**6.43**
Ca	0.625		Heden.	**11.32**	0.650		Heden.	**6.25**
Na	0.350		Diopside	**49.60**	0.339		Diopside	**54.76**
K	0.000				0.000			
		tsch. first	Jadeite	**32.43**		**tsch. first**	Jadeite	**23.95**
Mg No.	82.14	**(Fe''' in aeg)**	Aegerine	**1.13**	89.99	**(Fe''' in aeg)**	Aegerine	**8.61**
Fe'''/Fe''(%)	9.58		Tsch.	**5.57**	137.20		Tsch.	**6.43**
Z	2.000		Heden.	**11.32**	2.000		Heden.	**6.25**
Y	1.025		Diopside	**49.54**	1.010		Diopside	**54.76**
X	0.975				0.990			
		aeg. first	Jadeite	**33.85**		**aeg. first**	Jadeite	**25.32**
			Aegerine	**1.13**			Aegerine	**8.61**
			Tsch.	**5.20**			Tsch.	**5.99**
			Heden.	**11.32**			Heden.	**6.25**
			Diopside	**48.50**			Diopside	**53.83**

Pyroxene end members :

jd.	NaAlSi2O6
aeg.	Na(Fe''',Cr)Si2O6
tsch.	(Ca,Mg)(Al,Fe''',Ti)(Al,Si)O6
hed.	Ca(Fe'',Mn)Si2O6
diop	(Ca,Mg)MgSi2O6

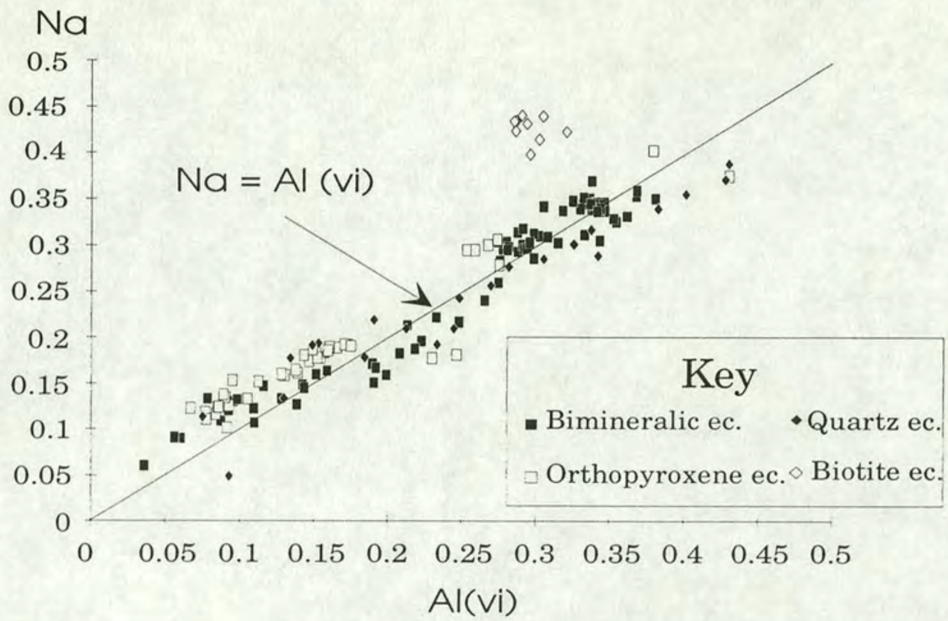


Figure 5.13 Na vs Al_{vi} for eclogite clinopyroxenes. With the exception of biotite eclogite, Na content ≈ Al_{vi} content for all eclogite clinopyroxenes, although in general Na content is slightly greater than Al_{vi}, implying that there is a small NaFe''' (aegerine) component. Note that the more Na, Al_{vi} rich pyroxenes from the bimineralic eclogite have Na > Al_{vi} whilst Na, Al_{vi} poorer compositions have Al_{vi} > Na.

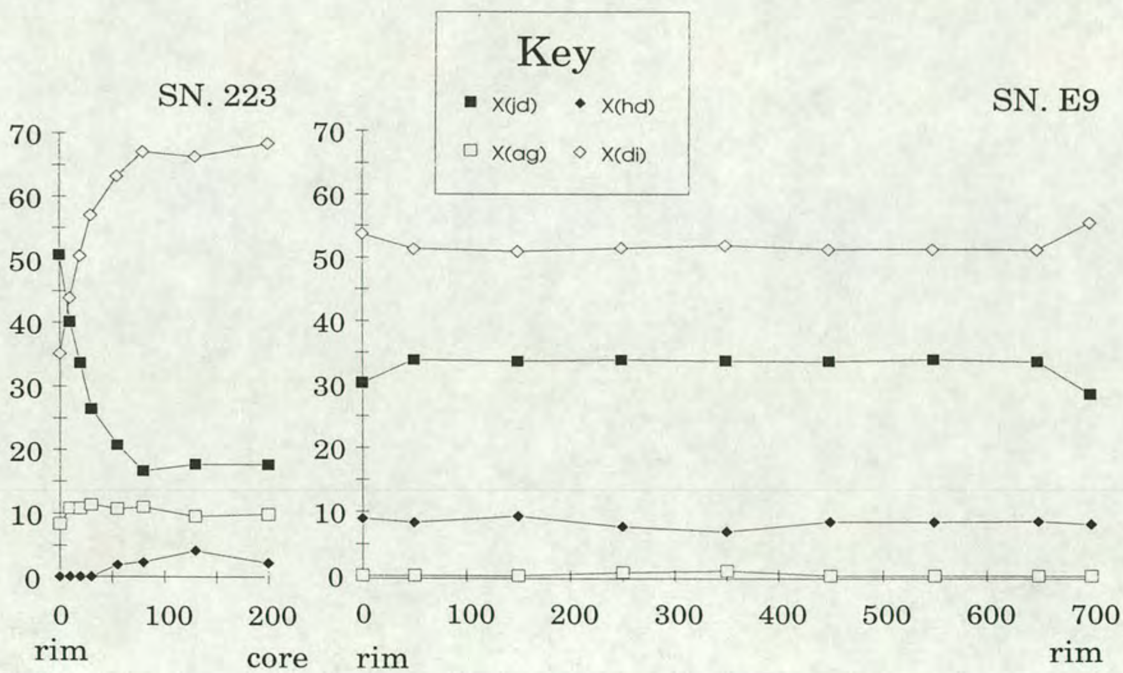


Figure 5.14 Profiles across clinopyroxenes from two eclogites. SN. 223 is an orthopyroxene eclogite with QFK streaks, the profile being from the rim of a pyroxene at the edge of a QFK streak, showing a strong decrease in jadeite content within 100 μm of the streak. SN. E9 is a bimineralic eclogite, showing a flat clinoypyroxene profile, apart from slight lowering in jadeite at the grain rim.

Figure 5.14 shows profiles across two eclogite clinopyroxenes. That from SN. E9, a bimineralic eclogite, shows a homogenous core, with slightly lower jadeite content at grain rims. SN. 223 is from the rim of a QFK streak across an orthopyroxene eclogite. This has a high jadeite content at the grain rim that drops off extremely rapidly to a relatively jadeite - poor core, consistent with the formation of pyroxene from the breakdown of plagioclase, suggested by Sanders (1988).

Figure 5.15 shows clinopyroxenes from the bimineralic eclogite. Core compositions are the most Al_{vi}, and hence jadeite, rich. Some core compositions are similar to rim compositions. Both coarse and fine grained symplectites were described in chapter four. The former tend to have higher Al_{vi} content than the latter. Figure 5.16 compares clinopyroxenes from the other eclogite types with those from the bimineralic eclogite. In general, they show a similar range of compositions, all of roughly similar Fe''' content, but for the biotite eclogite, which contains Fe''' rich clinopyroxene. Both quartz and orthopyroxene eclogites contain QFK streaks and rounded patches, and clinopyroxenes from the rims of these streaks are the most Al_{vi} rich. Symplectite clinopyroxenes are Al_{vi} poor.

Trace element compositions for clinopyroxene show slight enrichment of many MREE's in both bimineralic eclogite and eclogites with QFK streaks, although concentrations are generally very low (figure 5.17.A & B).

5.3.4 Orthopyroxene

Orthopyroxene from all three orthopyroxene - bearing eclogites is of fairly constant composition at about 80% enstatite. Mercy and O'Hara (1965) described orthopyroxene of about 85% enstatite within a two pyroxene rock, and O'Hara (1960) orthopyroxene of 70% enstatite in an iron - rich orthopyroxene - eclogite. Al contents are negligible.

5.3.5 Amphibole

In chapter four, three main types of amphibole were outlined: primary brown amphibole that occurred with or without biotite and plagioclase, possibly related to the formation of QFK material; secondary amphibole that resulted from the initial alteration of eclogite facies minerals; and tertiary amphiboles that occur within cracks cutting across the eclogite, often with either epidote or plagioclase.

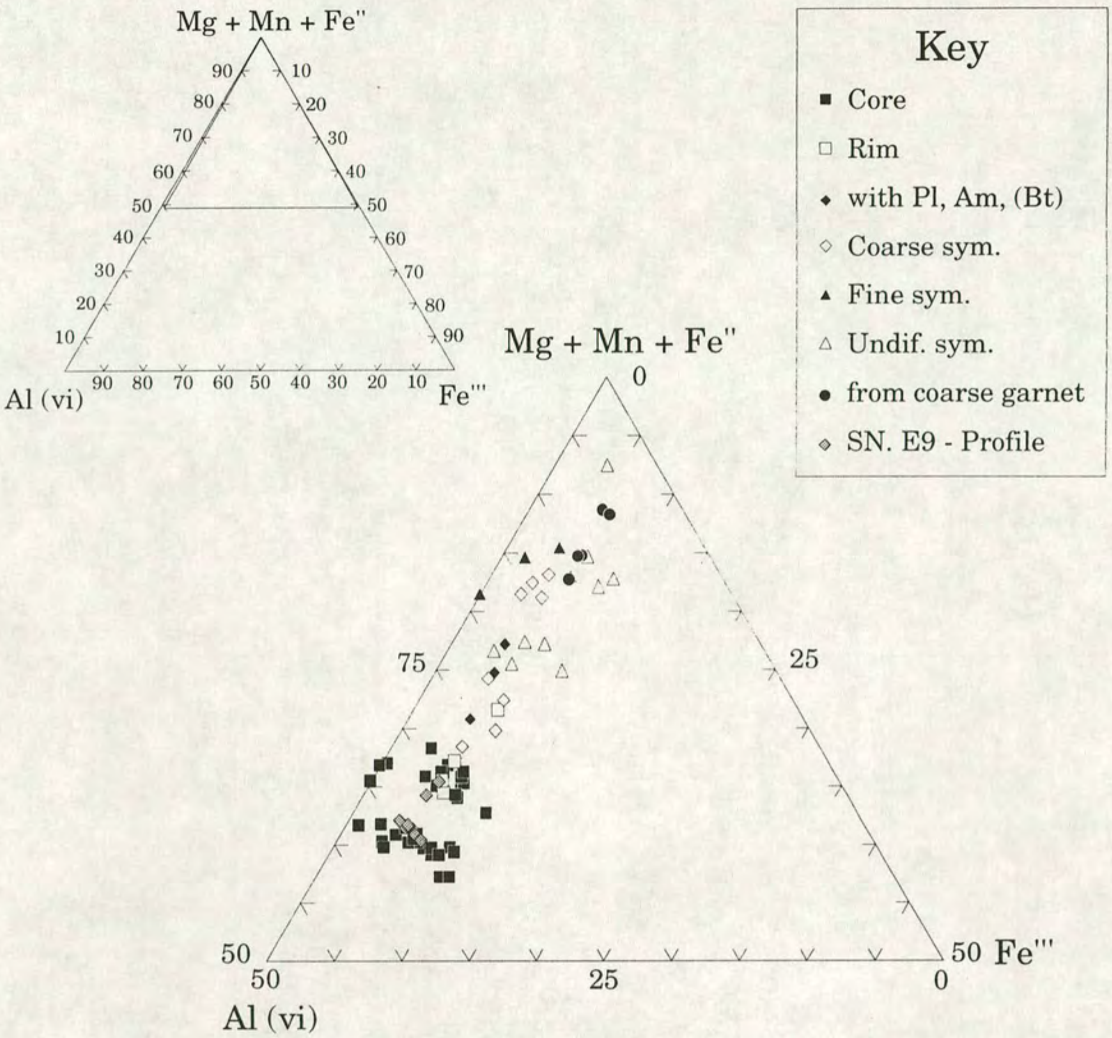


Figure 5.15 MMF - Al_{vi} - Fe''' plot for clinopyroxenes from bimineralic eclogites. Clinopyroxenes from bimineralic eclogites fall into distinct compositional groups, with Al_{vi} rich cores and slightly Al_{vi} poorer rims, demonstrated in figure 5.14. In figure 5.13 it was demonstrated that Al_{vi} content can be equated with jadeite content, thus cores have a jadeite content of up to 35 %, whilst rims are up to 30 %. Coarse symplectites generally have higher Al_{vi} content than finer symplectite, suggesting that they formed at higher pressure.

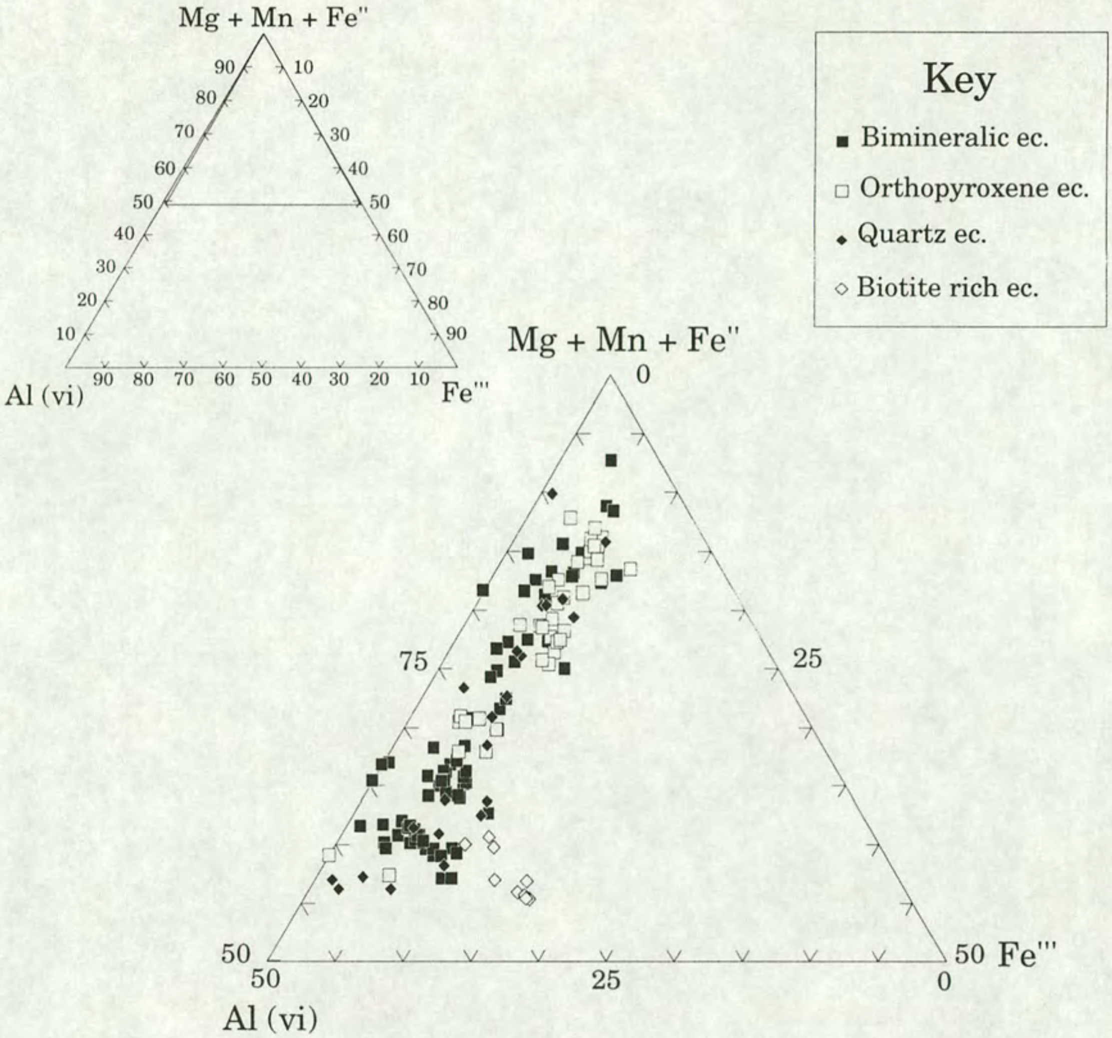


Figure 5.16 MMF - Al_{vi} - Fe''' plot for clinopyroxenes from all eclogite types. Fe''' content is fairly constant for each eclogite type, with a large range of Al_{vi} content. Clinopyroxenes from orthopyroxene and quartz eclogites show a similar range of compositions to those outlined for the bimineralic eclogite in figure 5.14. Clinopyroxenes from the biotite eclogite are Fe''' rich, and are of approximately constant Al_{vi} content. In section 5.2 it was shown that the biotite eclogite is Fe rich, reflected in the high Fe''' (and Fe'') content of the clinopyroxenes.

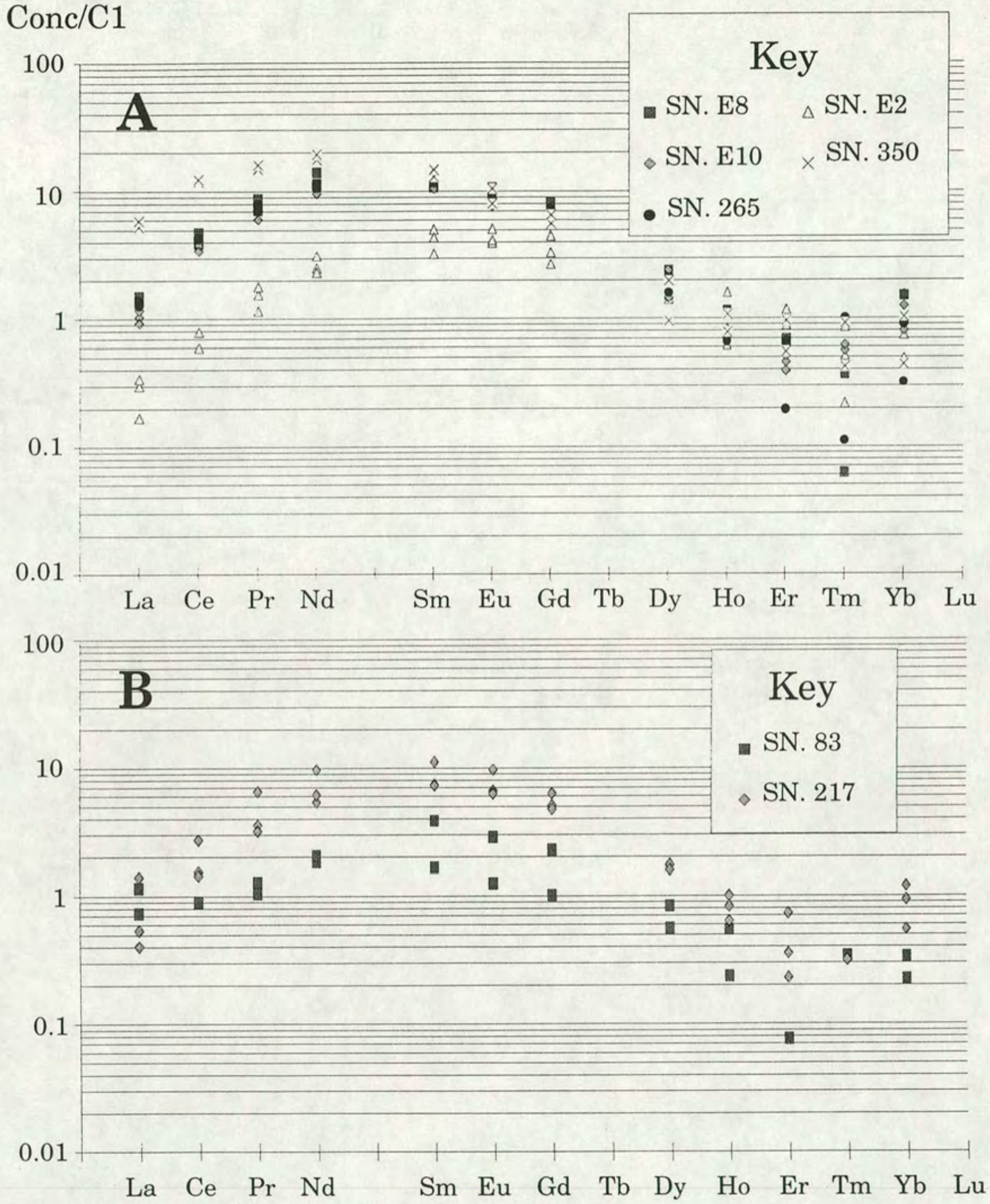


Figure 5.17 REE compositions of clinopyroxenes from eclogites, normalised to C1 chondrite values. Clinoyproxenes from all eclogites analysed are of similar composition, being LREE rich, particularly from Pr - Gd, although, on the whole, all are fairly REE poor.

Amphibole has the general composition $A_{0-1}X_2Y_5Z_8O_{22}(OH,F,Cl)_2$, where A is (Na,K), X is (Ca,Na,Mg), Y is (Mg,Fe'',Mn,Al,Fe''',Ti) and Z is (Si,Al). Because of site vacancies, it is virtually impossible to obtain accurate Fe''' content of amphiboles from electron probe analyses. Robinson *et al.* (1982) suggests methods of doing so to provide 'best - guess' estimates of Fe''' which have been used for samples in this thesis, based upon ignoring cations in either the X and/or A sites and assuming that there are no vacancies in the Y and Z sites. From the simple calcic - amphibole composition $Ca_2Mg_5Si_8O_{22}(OH)_2$, tremolite, three main substitutions are possible: $Mg_YSi_Z \Leftrightarrow Al_YAl_Z$, to produce tschermakite, $\blacksquare_ASi_Z \Leftrightarrow Na_AAl_Z$, to produce edenite, and $\blacksquare_A(Ca_2)_X \Leftrightarrow Na_A(NaCa)_X$, to produce richterite. In all cases there are also substitutions of Fe'' for Mg and Fe''' for Al. Substitution of Ca_X by Mg is also possible, to produce cummingtonite.

Amphiboles within the Eastern Lewisian occur over a wide range of compositions, almost all of which are Ca - amphiboles of Leake (1974). Amphiboles from each of the eclogite types have different compositions, but amphiboles of each type, primary, secondary and tertiary also have different compositions, best seen within the bimineralic eclogites. Figure 5.18 shows amphiboles from these eclogites. Primary amphibole and secondary amphibole resulting either from garnet or clinopyroxene alteration have distinct compositions, those secondary amphiboles after garnet being the most pargasitic. Tertiary amphiboles have a wide range of compositions. Figures 5.19 - 21 plot amphiboles from different eclogite types, and plot tertiary amphiboles from different eclogite types compared with amphiboles from Eastern Lewisian amphibolites. The compositions of tertiary amphiboles occurring in veins across all eclogite types is similar to those of secondary amphiboles from the same eclogite type. Amphiboles from the bimineralic eclogite are the most pargasitic, the most Al_{iv} rich, whilst those from the other eclogite types are broadly similar in composition to each other, although those from quartz eclogites are lowest in Mg content, probably reflecting bulk rock chemistry. Amphiboles from the amphibolites are generally have the lowest Al_{iv} content, and range towards actinolite.

Trace element compositions for amphiboles for primary amphiboles from bimineralic eclogites show them to have similar REE traces to pyroxenes from the same rocks, figure 5.22.A. Amphibole occurring in veins cutting across a bimineralic eclogite sample, SN. 353, have different, depleted, LREE's (figure 5.22.B).

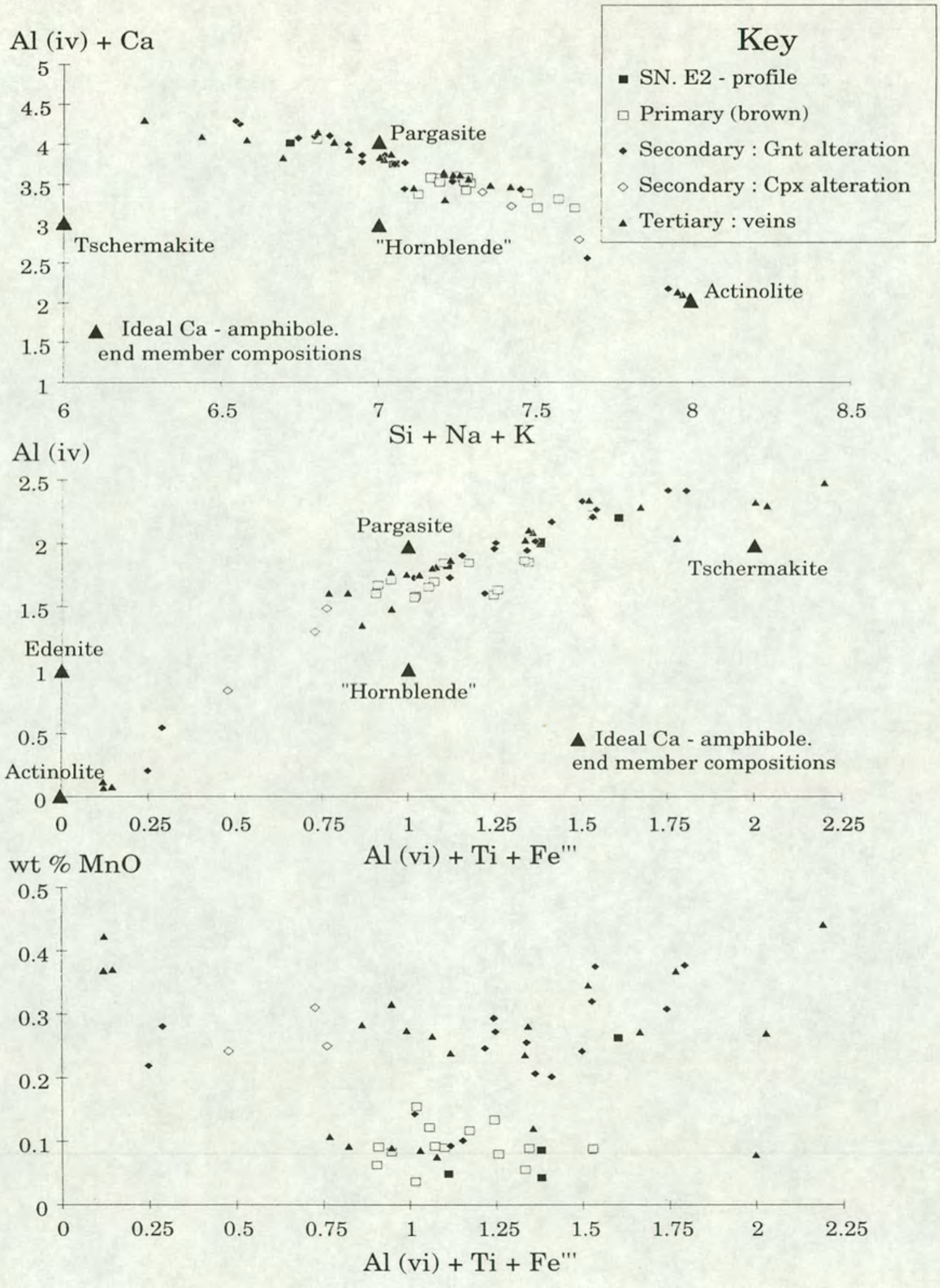
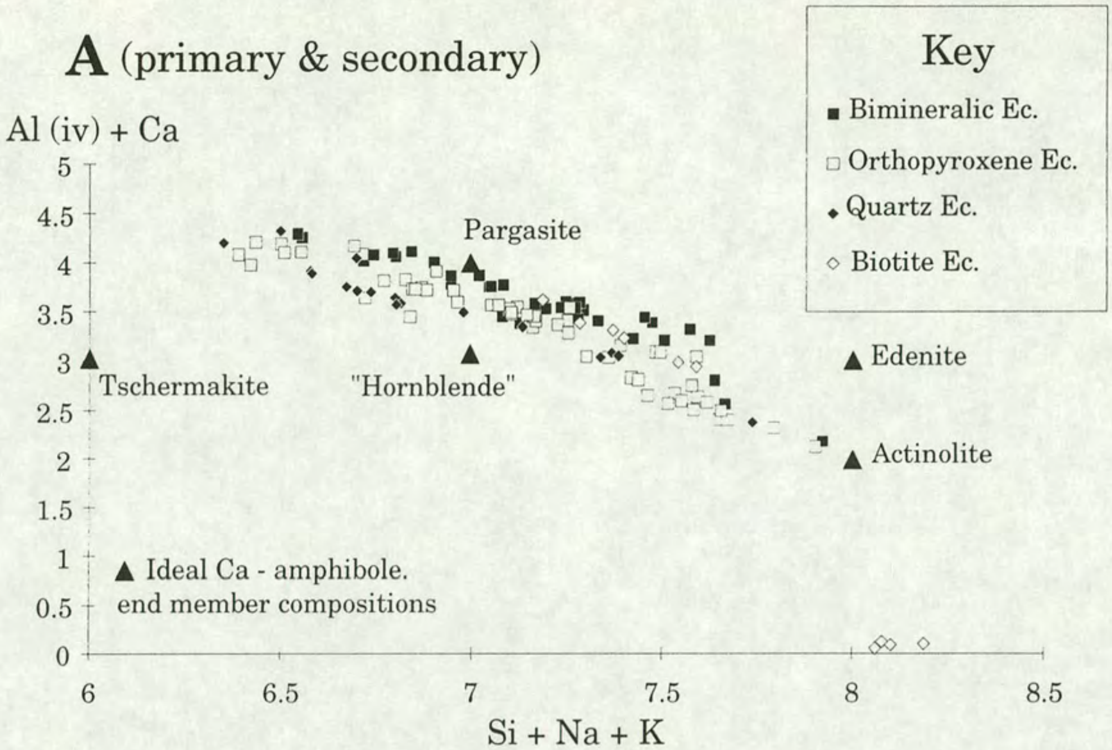


Figure 5.18 Amphiboles from bimineralic eclogites. Four types of amphibole can be identified from petrology, primary brown amphibole, secondary amphibole from garnet and from clinopyroxene alteration, and tertiary amphibole filling veins across the eclogites. Tertiary amphiboles have a wide range of compositions, ranging towards actinolite. secondary amphibole after garnet and after clinopyroxene have distinct compositions, the former being more pargasitic. Primary amphiboles have compositions between these, but in particular are MnO poor.



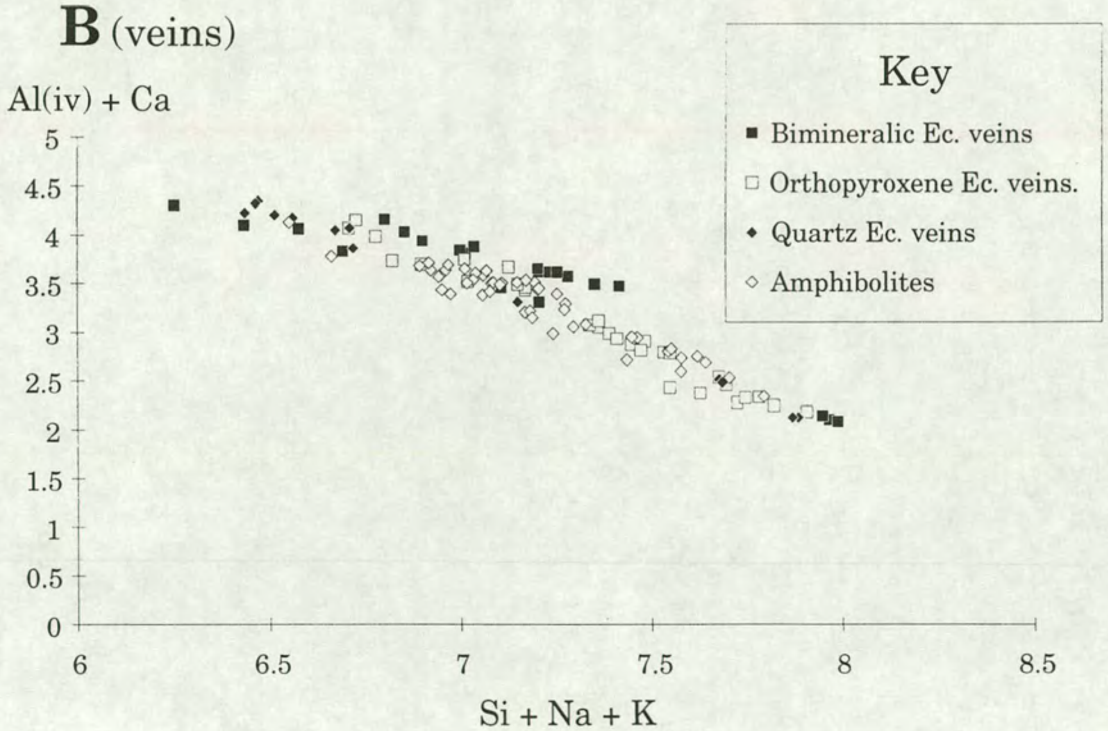


Figure 5.19 Amphiboles from Eastern Lewisian mafic rocks. A : Bimineralic eclogites are the most Al_{vi} - Ca rich. Quartz eclogites and orthopyroxene eclogites have similar compositions as each other. **B :** Amphiboles within veins from different eclogite types have different compositions, with those from the bimineralic eclogite again having the most Al_{vi} - Ca rich compositions. Amphibolies from various amphibolites derived from the eclogites are generally Al_{vi} poor, Si rich.

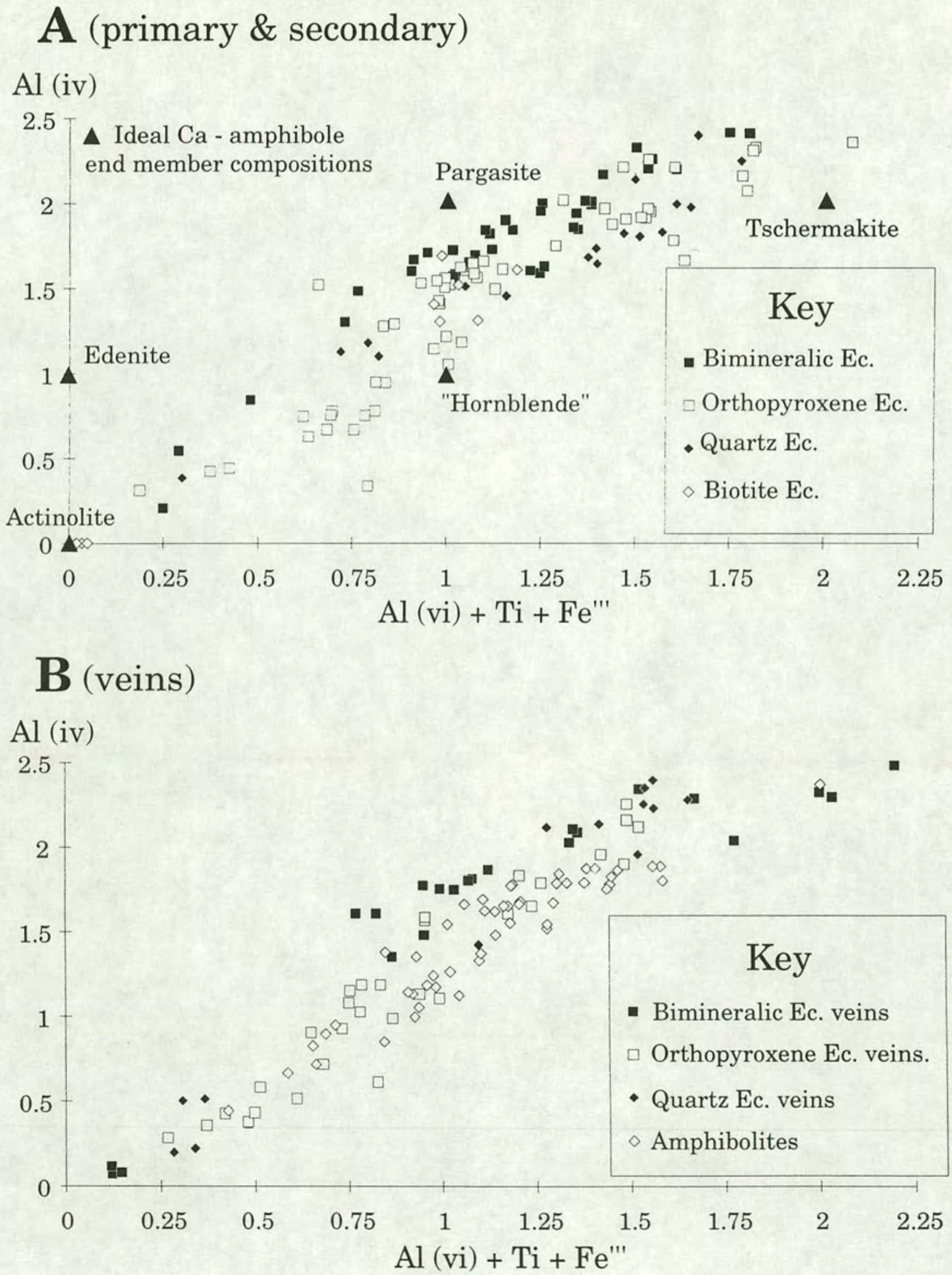


Figure 5.20 Amphiboles from Eastern Lewisian mafic rocks. As figure 5.19.

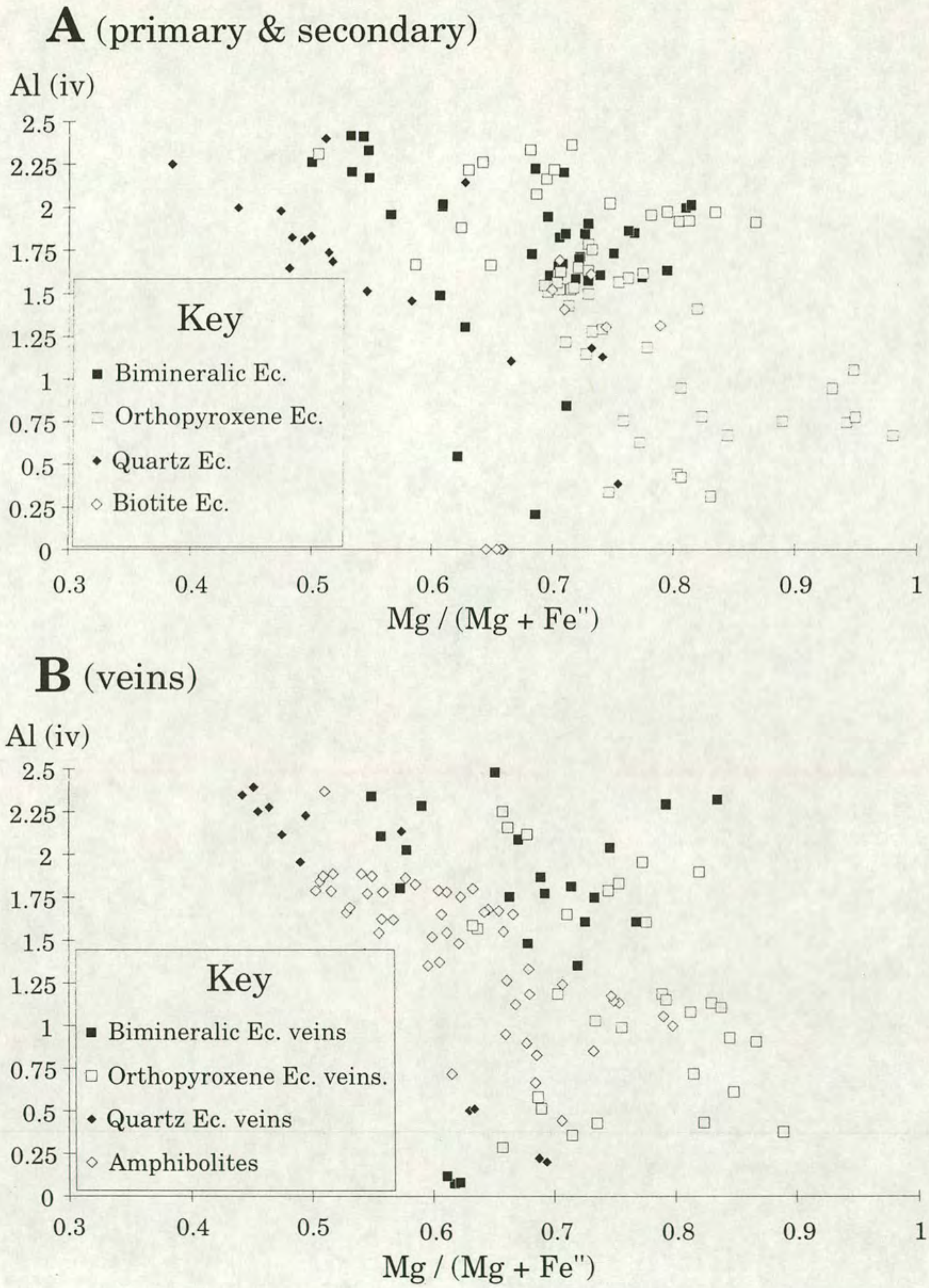


Figure 5.21 Amphiboles from Eastern Lewisian mafic rocks. Quartz eclogites are lowest in Mg, orthopyroxene eclogites highest in Mg, reflecting bulk rock compositions.

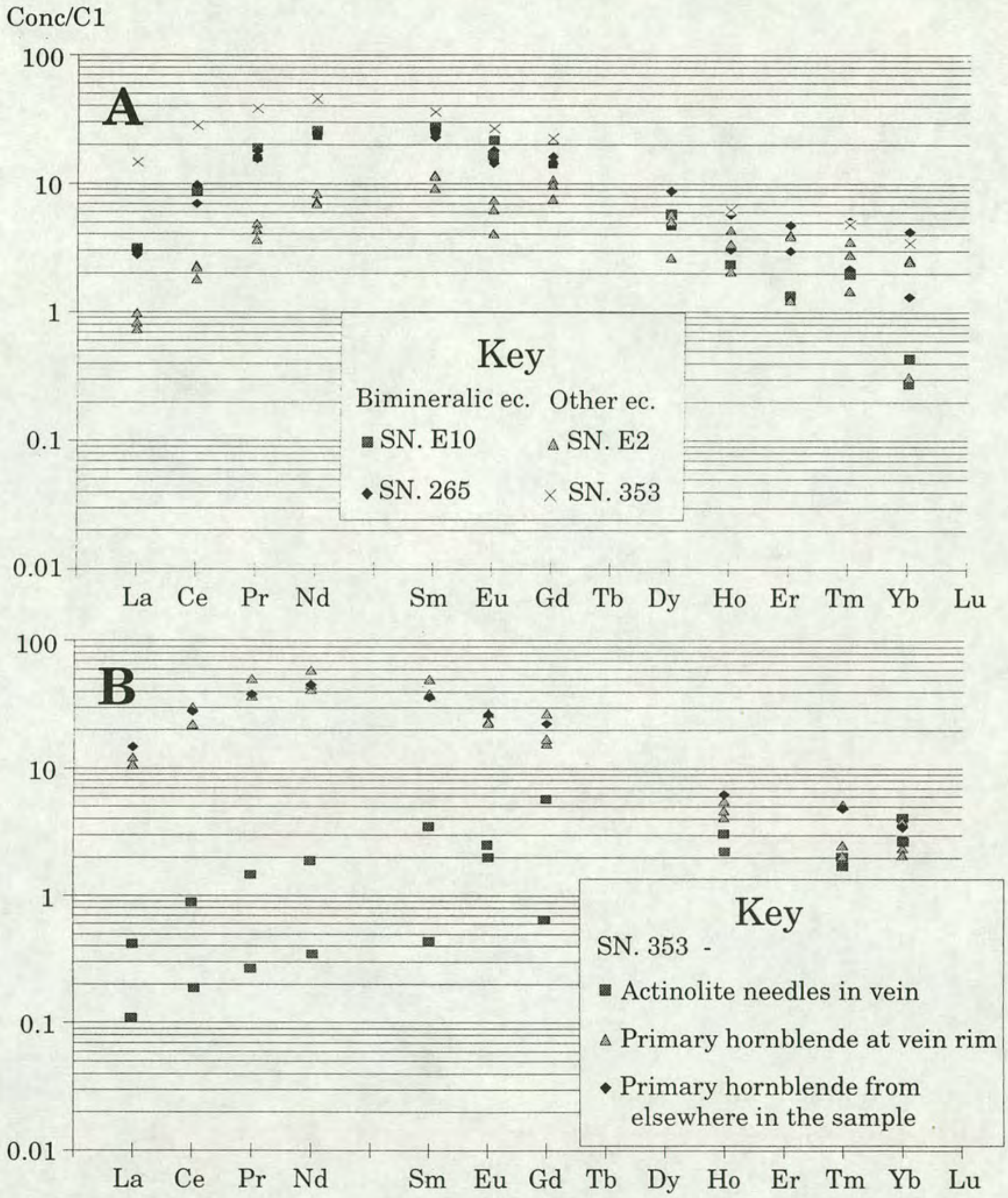


Figure 5.22 REE compositions of amphiboles from Eastern Lewisian eclogites, normalised to C1 chondrite values. A: Primary amphiboles within the bimineralic eclogite show REE trends similar to clinopyroxene, with slightly enriched LREE's from Pr - Gd. All show a small negative Eu anomaly, most visible in SN. E2, which also contains biotite and plagioclase. **B:** Amphiboles within actinolitic veins cutting SN. 353 have different REE traces to primary brown amphibole cut by the vein and occurring elsewhere within the sample.

5.3.6 Other phases

Rutile and **quartz** occur in minor amounts in all rocks. **Sphene** occurs as a secondary mineral from alteration of rutile and is Al poor. **Plagioclase** occurs throughout the eclogites as an alteration product of both garnet and pyroxene. Plagioclase from the alteration of garnet is of An_{55-65} (labradorite), regardless of eclogite type. All other plagioclase within the eclogites and related rocks (except within QFK streaks), whether in symplectites, or in the body of the rocks is generally of composition An_{15-20} (oligoclase). **Biotite** occurs in all the eclogites, either as an early mineral apparently corresponding to the QFK streaks, or as an alteration product of garnet. In most cases, biotite has approximately 3 weight % TiO_2, but in the iron - rich eclogite it is higher, up to 4 weight %, and in some quartz - eclogites it is much lower. Most biotites have a Mg no. of about 55 - 60%, but this is much lower in quartz - eclogites, only about 45%, and higher in the biotite - rich eclogite, 65%. **Epidote** group minerals occur as a breakdown product of garnet with amphibole. They are generally Fe''' poor, with a maximum of 0.4 ions of Fe''' per formula unit. **Scapolite** occurs within some quartz - rich eclogites, of composition $meionite_{45-55}$ (Ca - CO_3 component).

5.3.7 Quartz - feldspar - kyanite streaks

QFK streaks are composed predominantly of quartz, kyanite, K - feldspar and plagioclase, with or without garnet, rutile, sphene, ilmenite, biotite and amphibole entrained within them. The composition of garnet and clinopyroxene is discussed above. In general these minerals are Ca - and Na - rich respectively, due to the breakdown of anorthite and albite at high pressure (Sanders, 1988). Kyanite contains rare inclusions of plagioclase of An_{10-12} (oligoclase), and is invariably rimmed by plagioclase of An_{65-85} (bytownite). Plagioclase occurring within the streaks, but away from kyanite rims, is usually of composition An_{17-27} (oligoclase), roughly the same composition as that outwith the streaks. More calcic plagioclase occasionally occurs, generally with garnet, up to An_{55}, or with zoisite, up to An_{35}. In one sample (SN. 347) albite (An_{1-3}) occurred with quartz within the QFK streaks, whilst in rare samples albite (An_{6-8}) occurs as ex - solution laminae within K - feldspar. Primary, slightly pleochroic pink sphene is Al - rich with compositions of roughly $CaTi_{0.9}Al_{0.09}Fe'''_{0.01}Si(O,OH)_5$.

Kyanite has altered variously to plagioclase, margarite, muscovite and zoisite, discussed in chapter four above. Other than plagioclase, these minerals are of fairly constant composition, close to the ideal end - member compositions.

5.3.8 Origin of the QFK streaks

It was suggested by Sanders (1988) that QFK streaks represented the sites of former plagioclase within eclogites, and that during later high pressure metamorphism the anorthite broke down to form grossular and albite to jadeite. The latter statements have been confirmed, but the suggestion that the streaks represent the sites of former feldspar is questioned for three main reasons. Firstly the QFK streaks occur within both metasediments and metabasic rocks and streaks in the former appear to have behaved differently to feldspar in the bulk of the sediment. Secondly QFK streak rich eclogites have demonstrably Na, K, Al, Si rich bulk rock compositions compared to similar QFK streak free rocks suggesting that such elements may have been introduced into the rock after metamorphism. Thirdly, Sanders (1988) describes the streaks as only breaking down after initial eclogite facies metamorphism, during a later, slightly higher pressure phase of metamorphism. Original plagioclase within the rock would be expected to breakdown during the initial eclogite facies metamorphism of $\approx$ 730°C, 15 Kb, with, in particular, the alteration of albite to jadeite and quartz and this has apparently not occurred. Other evidence related to garnet compositions, outlined in section 5.3.1, suggest that the occurrence of quartz eclogite, of QFK streaks and of brown primary amphibole may all be related.

Whilst it is not categorically stated that no QFK streak was the site of original plagioclase within the rock, as suggested by Sanders (1988), it is felt that the intrusion of quartzo - feldspathic material into the eclogite after initial metamorphism, with some extensive recrystallisation during later eclogite facies metamorphism, would better explain the points raised above.

5.3.9 Thermobarometry

Calculation of pressures and temperatures of formation of the eclogites is discussed in chapter ten. In summary there appear to be two distinct episodes of metamorphism, one at $\approx$ 730°C,>15 Kb, the other at $\approx$ 780°C,>17 Kb, the latter affecting QFK streaks and bimineralic eclogite with primary amphibole. Retrogression appears to have occurred at above 600°C.

5.4 Conclusions

Much of the history of the eclogites relies upon the interpretation of garnet compositions. Sanders (1988) suggested that Ca - rich garnet grew from the breakdown of anorthite within QFK streaks. This undoubtedly occurred, and in some rare quartz - eclogites, e.g. SN. 83, there are only Ca - rich garnets and Na - rich clinopyroxene. Evidence from garnet compositions suggests that at least some quartz eclogites may well result from large scale recrystallisation related to the alteration of plagioclase within QFK streaks. It also appears that the occurrence of brown amphibole within some bimineralic eclogites is also related to availability of Ca during a second phase of high pressure metamorphism. Some rocks are thus thought to represent areas in which large volumes of QFK material existed, possibly due to intrusion of that material. However, there are many occurrences of garnet and clinopyroxene within QFK streaks having compositions similar to garnet and clinopyroxene in the host rock. This implies that the crystals were entrained within the streaks, and did not grow within it, suggesting that the streaks may have been forcibly intruded into the basic host rock. The streaks are thus apparently intruded into already metamorphosed basic rock in variable amounts, and then metamorphosed along with it.

Clinopyroxene compositions have been discussed in detail by most previous workers, particularly Alderman (1938) and Sanders (1972, 1978). They are all omphacitic pyroxenes that have altered to form augitic pyroxene in symplectites with plagioclase. However exsolution of rutile and sphene is common in many pyroxenes, particularly those from orthopyroxene - bearing eclogites, suggesting that some eclogite pyroxenes may have originally had high Ti content, indicative of pyroxene crystallising within alkali - basaltic rocks. Both clino - and ortho - pyroxene in SN. 511 contain lamellae of exsolved Mg - rich garnet. Garnet exsolved from cumulate pyroxenes tends to be Ca - rich (Sanders, 1978), but Lappin (1973) suggested that for unusual eclogite bulk - rock compositions (other than garnet - clinopyroxene - quartz, with or without kyanite and rutile) at high pressure or temperature, clinopyroxenite would probably form and that garnet. and/or orthopyroxene would exsolve from the clinopyroxene matrix at lower temperature.

Chapter Six

Petrology and geochemistry of other Eastern Lewisian rocks

CHAPTER 6

Petrography and Geochemistry of other Eastern Lewisian rocks

6.1 Introduction

In chapter three the field occurrence of the eclogites and related rocks from the Eastern Lewisian was described, along with a brief mention of the more important outcrops of other rock types, principally metasediments. The petrography and chemistry of the eclogites were described in chapters four and five respectively. In this chapter the petrography and chemistry of the other Eastern Lewisian rock types will be described and compared to the eclogites.

Other mafic rock types include ultrabasic pyroxenites and rare amphibolites that do not appear to be related to the eclogites. These latter are important in interpreting the history of these rocks. The non - mafic rocks can be divided into five groups: metapelites, eulysites (Fe, Mn - rich metasediments), marbles, quartzo - feldspathic rocks and graphitic schists. The latter are not considered further due to lack of sampling or reference in the literature. Of the other rock types, this thesis has concentrated mainly on nodules within the marble and on the pelites. The petrology and chemistry of each of the rest of these groups will be described in turn, followed by a short summary of their inferred history. Analytical procedures are described in appendix II. Representative mineral analyses from each rock type are in appendices III and IV. All these rocks were described by the geological survey (Peach *et al.*, 1910, May *et al.*, 1993). Sanders (1972) described fresh, unretrogressed samples of each of the metasediment types. The eulysites were described in detail by Tilley (1936), the marbles by Rock (1987).

All plots of mineral analyses for any one group of rocks contain more than one analysis from each sample analysed, often with more than one analysis from any one grain.

6.2 Metapelites

A number of types of garnet - biotite - quartz - feldspar rock occur throughout the Eastern Lewisian. For the purposes of description all will be described below as metapelites, but for many of the Eastern Lewisian rocks it is almost impossible to identify an original protolith, and it is likely that some of the rocks described below were of igneous origin, and represent metamorphosed acid igneous rocks rather than metamorphosed sediments. Sanders (1989) assumed that all garnet - biotite - feldspar - quartz - (kyanite) rocks were of igneous origin. Two bulk rock analyses from May *et al.* (1993) are given in appendix III.

6.2.1 Petrology

One of the best places to observe the metapelites is at Drum Iosal, GR 857161, where they show a wide variety of textures. They are garnet - biotite - quartz - feldspar rocks in various states of deformation and with or without kyanite (plate 6.1.A).

Fresh samples, such as SN. 7, contain large, often skeletal, garnets up to 5 mm across full of square inclusions of quartz and biotite (plate 6.5.B). The matrix of the rock is composed of elongate wisps of fox brown biotite, invariably all aligned, along with anhedral crystals of quartz and feldspar. Rutile is invariably rimmed by ilmenite. Not all samples are kyanite - bearing, but those that are, such as SN. 8, contain large skeletal crystals of (plate 6.1.B). Both kyanite and garnet contain many square inclusions of quartz and biotite. Kyanite occasionally forms a coarse symplectite with quartz. Garnet and kyanite are rarely cracked, but when they are the cracks contain biotite. Kyanite is altered at its rims to a thin rind of white mica. Some samples, such as SN. 10, contain streaks of quartz - feldspar - kyanite (QFK), similar to those described in chapter four, above, for the eclogites. Quartz and feldspar have a polygonal texture with small stubby crystals of kyanite between. In places patches of coarse kyanite and feldspar exist. This latter is often altered to fine grained white mica. Quartz and feldspar occur separately (plate 6.5.A).

Most quartz inclusions within the garnet have plagioclase moats, although much of this plagioclase is now altered to fine grained sericite. The garnets are extensively cracked, with up to 50% of the original crystal made up of cracks filled by biotite, which is normally fox brown, but sometimes pale green. Very occasionally lines of small quartz inclusions indicate possible overgrowths similar to those seen in the eclogites. At the edge of the QFK streaks small subhedral garnets often occur, sometimes filled with tiny quartz inclusions. Garnet is also altered at its rims to fox brown biotite, with much of the matrix around the garnet composed of biotite, quartz and feldspar, that is difficult to distinguish from the QFK streaks.

Whilst some samples are relatively undeformed, many have been strongly deformed, both folded and sheared, often with two fabrics. In these no garnet or kyanite is seen, the rocks consist entirely of biotite, quartz and feldspar. The biotite is often dark green - brown, and outlines a strong fabric. Where the rocks are folded the biotite forms chevron folds, and is usually not recrystallised parallel to the hinges (plate 6.5.C). Quartz and feldspar both occur as large anhedral crystals.

SN. 271 from GR. 869242, south of Loch Duich, consists almost entirely of garnet. Between individual garnets are small amounts of quartz, biotite and rutile. Rare cracks are filled with green chlorite and ilmenite. In parts, plagioclase - quartz streaks cut across the rock. At the rims of these the garnet is subhedral and often contains tiny quartz crystals indicating overgrowths (plate 6.1.C).

Most of the garnet - biotite - quartz rocks in the Eastern Lewisian are kyanite free. Many of these consist of large cracked garnets in a matrix of quartz, feldspar and biotite occasionally cut by QFK streaks. Other types are more quartz - feldspar rich, with small biotites and garnets. In many of these rocks, patches of coarse feldspar - white mica occur, with the mica occurring as stubby crystals either between polygonal feldspars or as inclusions within coarse grained feldspar.

The garnets in those metapelites with small garnets and a high proportion of quartz and feldspar have textures similar to those in the coarse grained rocks described above. The garnets are generally rounded, inclusion free and cracked. Usually they are altered to chlorite, both in cracks and at crystal rims. The matrix is made up of quartz, feldspar and muscovite, with rare biotite and ilmenite. In other rocks, such as SN. 98, from north of Glen Beag, small subhedral garnets occur, often altered to biotite (plate 6.2.B). These occur in a weakly foliated rock consisting largely of strained elongate crystals of quartz and feldspar, with small stubby kyanite and muscovite crystals defining the fabric, and with rare biotite. Sometimes garnet is completely replaced by biotite and plagioclase.

In section 3.2, above, at the top of the cliff at Lochan na Beinne Faide, the variation in the composition of a metapelite between thick bands of eclogite and marble was noted. SN. 318 from close to the eclogite consists of large round cracked garnets, full of small inclusions of quartz and biotite, and with little alteration along the cracks. Rare large round inclusions of quartz occur. All of the garnets are rimmed by and partly altered to dark brown biotite (plate 6.1.D). Rutile is rare and has mostly been altered to ilmenite. Between the garnets are patches of quartz and feldspar, mostly consisting of large polygonal grains. White mica occurs sporadically throughout the rock. SN. 315 from close to the marble consists of small cracked garnets altered at the rims and in cracks to green biotite. Rutile is partly altered to ilmenite. Between the garnets are large patches of polygonal quartz and feldspar with no biotite or ilmenite. At the garnet rims are patches of ragged quartz and feldspar, white mica, biotite and ilmenite. SN. 316 from the middle of the outcrop consists of large rounded garnets, that are cracked, but almost unaltered. They contain large inclusions of K - feldspar, and occasionally quartz and rutile. Often the rims of the garnets consist of small subhedral garnets with quartz. Most of the rock consists of polygonal quartz and feldspar with rare biotite and ilmenite defining a weak fabric wrapping about the garnet (plate 6.2.A). In all these samples K - feldspar is the dominant feldspar.

6.2.2 Chemistry

The main constituents of the metapelites are garnet, biotite, K - feldspar, plagioclase and quartz. **Garnet** is grossular poor, with a maximum of 20% Ca - end members. All the metapelitic garnets, from both kyanite - bearing and kyanite - free rocks, have broadly similar compositions to each other, with trends from Mg rich cores to Fe rich rims, and some variation in Ca content, figure 6.1, but not as clear as that seen in the eclogite (section 5.3.1). Figure 6.2 shows profiles across garnets from four samples. All but SN. 315 have reasonably flat, MgO rich cores and FeO, MnO rich rims. SN. 315 has a fairly flat profile with slightly FeO poor rims.

Biotite is of variable composition. For most of the metapelites, Mg nos. are about 0.55 - 0.65. However those biotites from the Lochan na Beinne Faide rocks have variable Mg nos. of about 0.4 - 0.45 for SN.'s 315 and 318, close to the marble and the eclogite respectively, and about 0.55 - 0.75 for SN.'s 316 and 317 in between. Ti content is also variable. For most rocks it is between 0.7 and 1.8 wt % TiO_2, although rare biotite inclusions within garnet often have higher contents. Of the Lochan na Beinne Faide

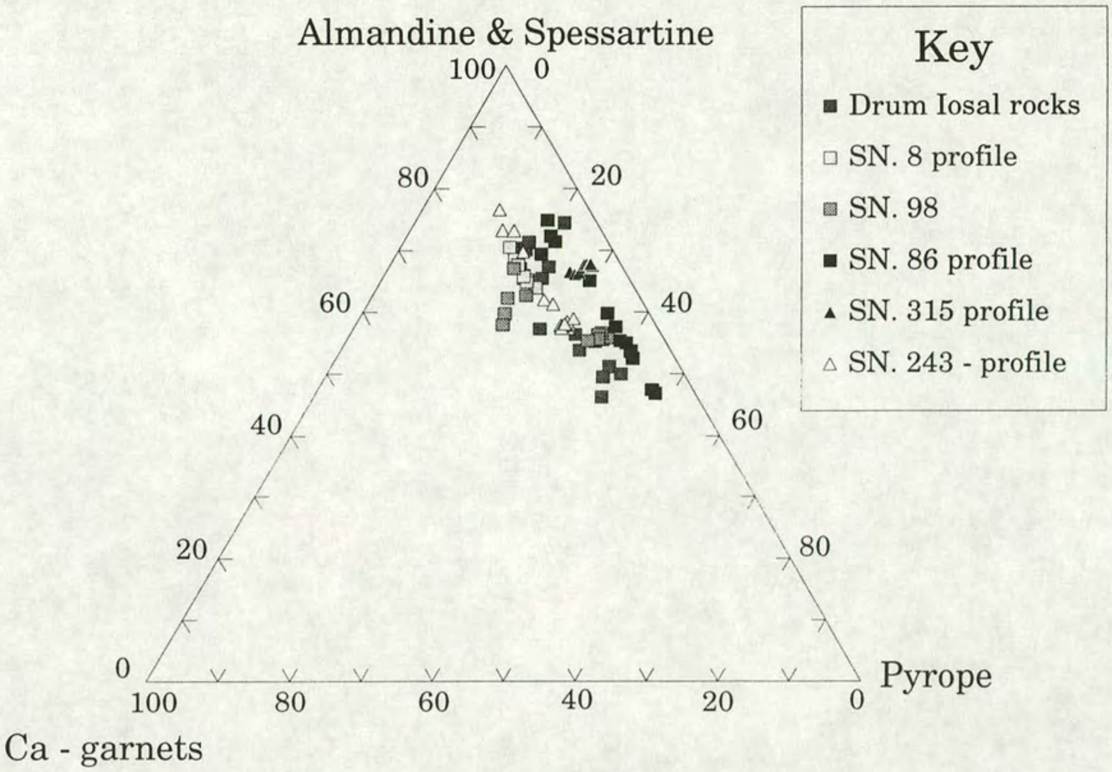


Figure 6.1 End member plot for garnets from Eastern Lewisian metasediments. There is a general trend from Mg rich garnets to Fe, Mn rich garnets. Rare samples show small changes in Ca content (see figure 6.2).

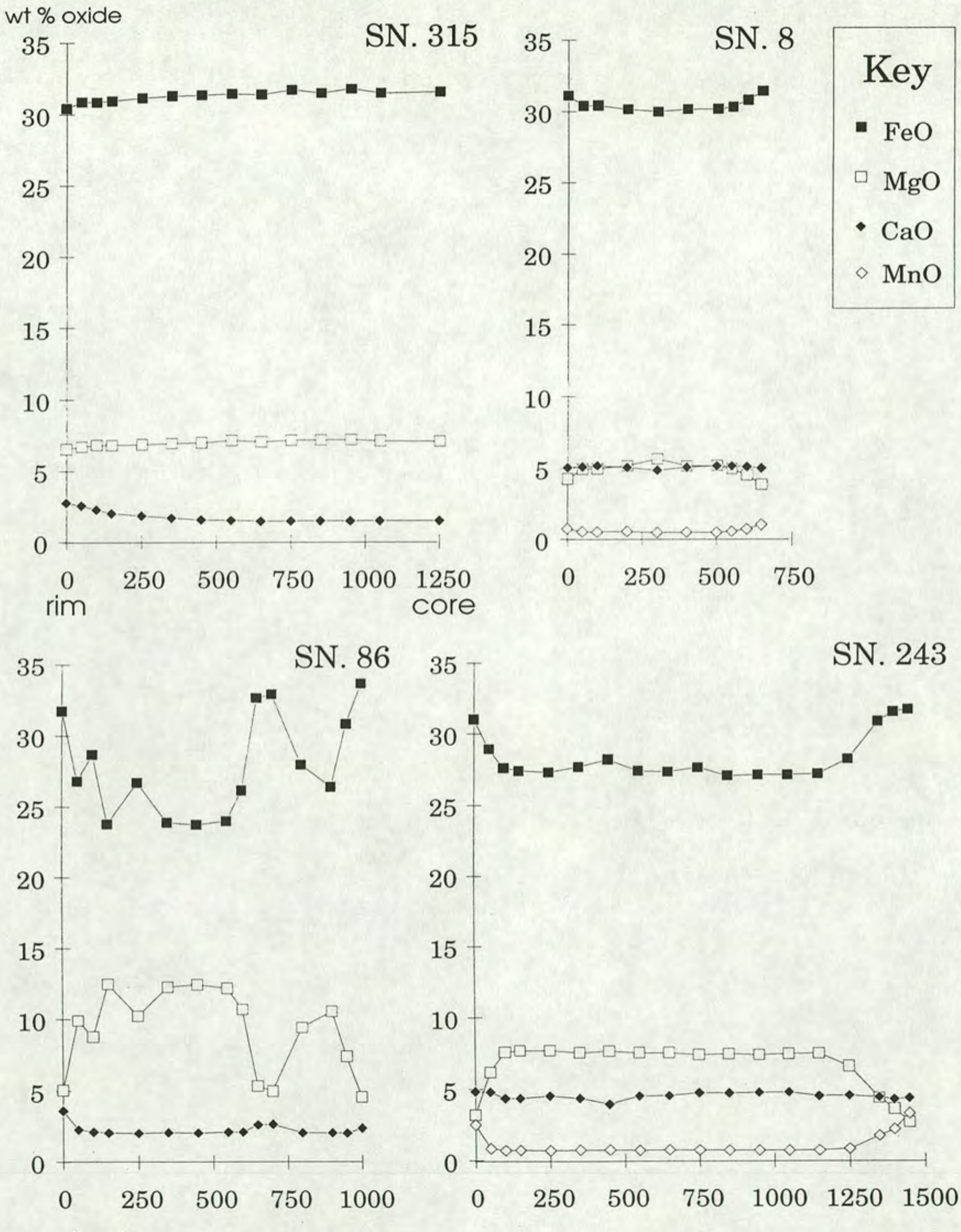


Figure 6.2 Profiles across garnets from four metasediments. The profile across SN. 315 is from rim (left) to core (right), the other profiles are from rim to rim. SN. 315 has a comparatively FeO rich core and CaO rich rim. The other three samples have comparatively FeO and MnO poor, MgO rich cores and FeO, MnO rich, MgO poor rims with little change in CaO content. SN. 86 in particular shows alteration to FeO rich, MgO poor compositions alongside cracks across the garnet, similar to many eclogite types, and also shows slight enrichment of CaO at garnet rims. MnO content is low in SN.'s 315 and 86 and is not plotted.

rocks, SN.'s 315 and 318 contain 0.9 - 2.2 wt % TiO_2, whilst 316 and 317 contain about 2.4 - 4.1 wt % TiO_2.

Plagioclase is also of variable composition. In most of the rocks it has a large range from An_{26-42} (oligoclase and andesine), but is mostly An_{26-31}. In the rocks from Lochan na Beinne Faide plagioclase is of composition An_{2-8} (albite) in all four samples.

6.2.3 Summary

The metapelites can be split mineralogically into three groups, garnet - biotite - quartz - plagioclase rocks that do or do not contain kyanite, and garnet - feldspar - quartz - rutile rocks.

Those, at Druim Iosal in particular, with kyanite and QFK streaks, can be loosely correlated with the eclogite history outlined in section 4.4.7, in that they are coarse grained, with QFK streaks, and are then recrystallised to form finer grained rocks prior to general deformation and retrogression. Other, more deformed rocks from Drum Iosal can be correlated with deformed eclogites. They show two fabrics, a weak early fabric wrapping around garnet porphyroblasts and a strong second fabric with lineation and with no remaining garnet. The second fabric is folded by tight brittle folds. The other rocks from Drum Iosal, with coarse grained sieve textured garnet and kyanite may represent recrystallisation of the sediments after the intrusion of QFK streaks. There is little doubt that the Eastern Lewisian eclogites and metapelites underwent similar histories.

Pressures and temperatures of formation are discussed in detail in chapter 10, but all the metasediments appear to have been metamorphosed at approximately 706 - 795°C, 10 Kb and at 633 - 667°C, also at 10 Kb, both calculated from garnet - biotite pairs. Pressure estimates are poor. These temperatures are thought to represent eclogite facies metamorphism and syn - Moine metamorphism respectively. It is thought odd that there is no alteration of albite to produce jadeite and quartz, even though the rocks were metamorphosed under similar conditions to the eclogites and QFK streaks, in which Sanders (1988) demonstrated that albite broke down.

6.3 Eulysites

6.3.1 Petrology

The eulysites of Glenelg were described by Tilley (1936). He recognised three types of eulysite: fayalite eulysite, hedenbergite - garnet rock, and grunerite - garnet rock. All three of these rock types are rich in MnO. This study has been restricted to the latter two types as no outcrop of the first sort was found. In general the eulysites are quartz free, but contain much apatite and either magnetite or ilmenite.

The fayalite eulysite was described by Tilley to be composed mainly of rounded grains of fayalite up to 0.5 mm across, and of clinopyroxene up to 3 mm across. Garnet is less common, but occurs with variable grain size, between 0.5 and 3 mm. Generally it is inclusion free, but rare inclusions of fayalite, clinopyroxene, apatite and magnetite occur. Magnetite usually occurs in bands wrapping around fayalite crystals, or else intergrown with garnet. Grunerite occasionally forms from the alteration of clinopyroxene. Rare orthopyroxene occurs, usually it is restricted to orthopyroxene - rich rocks, with minor garnet and clinopyroxene. In these, orthopyroxene occurs as large, strained, anhedral crystals 6 to 10 mm across in a finer grained polygonal groundmass of ortho - and rare clinopyroxene and garnet. Grunerite occurs in bands and veins across the rock.

The second sort of eulysite, a predominantly clinopyroxene - garnet rock, is far more common. Tilley describes this as being composed of either anhedral grains of clinopyroxene up to 4 mm across, or of aggregates of smaller clinopyroxene crystals. Garnet and magnetite are common, as is secondary grunerite, after clinopyroxene. Tilley describes this as a quartz free rock, but in places garnet - quartz - clinopyroxene rock has been found, such as SN. 95. In this the garnet occurs as large anhedral, zoned crystals, up to 2 mm across. The cores are inclusion free, and paler pink than the rims which are often ragged, and filled with tiny quartz inclusions (plate 6.2.C). Much of the rest of the rock is composed of interlocking polygonal grains of quartz, although rare larger strained crystals occur. These occur as thick veins with small garnets and grunerite. In places rounded quartz crystals are rimmed by garnet. Patches rich in clinopyroxene occur, with many anhedral crystals up to 1 mm across. Ilmenite occurs as rounded aggregates. Both grunerite and a green amphibole occur, the former is more common, and occurs at the rims of garnets along with quartz, and alongside the clinopyroxene. Rarely the cores of pyroxenes are altered to green amphibole. The entire rock is cut by veins filled with Fe oxide.

Tilley's third type of eulysite is the alteration product of his second type, the clinopyroxene - garnet rock described above. In these grunerite occurs as radiating aggregates of crystals pseudomorphing clinopyroxene, although coarse grained anhedral crystals of grunerite also occur. Garnet tends to occur throughout the rock as polygonal, inclusion free crystals less than 0.5 mm across. Quartz and apatite are also common. SN. 94 is similar to this, but with ilmenite throughout and with a second, green amphibole as well as colourless grunerite (plate 6.5.D). SN. 228 is a grunerite - garnet - apatite - ilmenite rock, consisting mainly of radiating aggregates of grunerite pseudomorphing a polygonal texture, outlined by relicts of ilmenite between the polygons (plate 6.2.D). Garnet and apatite occur throughout as rounded crystals up to 1 mm across, often as aggregates of three or more crystals.

6.3.2 Chemistry

The primary phases of the eulysite are garnet with either pyroxene or olivine. All phases are Mn rich. In this study no olivine bearing eulysites have been found, but Tilley describes the **olivine** as being fayalite with high Mn content. **Garnet** is ubiquitous. It is Mn rich, with a maximum of nearly 60% spessartine end member, but more normally 30 - 40%. There is virtually no pyrope, but the garnet shows variation in grossular and andradite contents. Garnet from quartz bearing eulysites have higher Ca content than others, figure 6.2. **Pyroxene** from SN. 95 is also Mn - rich and has almost no jadeite component, being mostly Fe - Mn hedenbergite. **Amphibole** is predominantly of the cummingtonite - grunerite series ($[Mg,Fe'']_7Si_8O_{22}(OH)_2$), but with high Mn content, up to 1.4 ions per 23 oxygens. Green amphibole in SN. 95, from the alteration of clinopyroxene, is of approximate composition $Na_{0.25}Ca_{1.7}([MgFeMn]_{5.2}Al_{0.1})(Si_{7.5}Al_{0.5})O_{22}(OH)_2$. This is compositionally between the cummingtonite amphiboles and the calcic amphiboles, with some (Mg, Fe'', Mn) in the X site. In SN. 95 **ilmenite** is of composition $Fe_{0.7}Mn_{0.3}TiO_4$.

6.3.3 Summary

Tilley (1936) implies that three sorts of eulysite exist within the Eastern Lewisian. The first sort are olivine - clinopyroxene rich rocks, with rare garnet and orthopyroxene, the second sort are orthopyroxene - rich rocks with rare clinopyroxene, the third sort are clinopyroxene rich rocks with rare garnet and orthopyroxene. The first and second sorts are only described by Tilley as unretrogressed specimens, whilst the third sort are described in less detail, but their retrogression is also briefly described.

Texturally, Tilley describes all the eulysites as changing from coarse grained rocks with large anhedral crystals to finer grained rocks with polygonal crystals, a general change similar to that seen in the eclogites. In this study the intrusion of quartz streaks is noted, although no feldspar or kyanite was seen. This is accompanied by overgrowths on garnet, and only small amounts of clinopyroxene in the rock, both features associated with the intrusion of QFK streaks within the eclogite. In other specimens of eulysite alteration occurs firstly by the growth of coarse grained grunerite, apparently in equilibrium with garnet and clinopyroxene, then later by alteration of garnet and clinopyroxene to green amphibole, or to fine grained aggregates of grunerite. This may correspond to the general hydration of the eclogites seen at Lochan na Beinne Faide, where brown amphibole is produced in equilibrium with garnet and pyroxene, prior to later general alteration of garnet and pyroxene to produce more amphibole.

6.4 Marbles, marble nodules and calc - silicates.

The marbles of Glenelg are heterogeneous in composition, varying from fairly pure dolomitic rock to a rock with variable proportions of calcite, olivine, diopside, white mica and tremolite, all of which occur either as large crystals or as nodules within the marbles. These were interpreted by Sanders (1972) as being former chert nodules. Nodules of other rock types also occur, most of which appear to resemble various of the eclogite types described in chapter 3 above. The occurrence of these nodules has not been described in detail before. Large nodules of calc - silicate rock up to 5 metres across also occur within and at the edges of the marble. The whole rock chemistry of two marble samples from May *et al.* (1993) are given in appendix III, along with a few of the marble nodules.

6.4.1 Marble petrology

Dolomitic marble without silicates is rare. Where it does occur, the rock consists of coarse polygonal grains of calcite and dolomite. These often have strain lamellae, and sometimes the calcite contains lamellae of dolomite.

Marble containing various proportions of other phases is far more common. The most common type of marble is a bimineralic calcite - olivine rock. Sometimes other minerals occur, including diopside, chlorite, white mica and rare spinel. In olivine bearing marble, olivine often forms up to 40 % of the rock. Fresh olivine is rare, occurring as large irregular rounded crystals. Even in the least altered rocks, the olivine is cracked and partly altered to serpentine. More commonly all the olivine is altered forming a serpentine - marble. The olivine is more rarely altered to humite and chlorite (plate 6.3.A). This alteration occurs in rocks where initial alteration of olivine to serpentine did not occur to completion. Other minerals more commonly occur as nodules within the marble rather than as single crystals.

6.4.2 Marble nodule and calc - silicate petrology

Nodules within the marble are common. They can be split into two sorts, nodules derived from the marble, generally composed of diopside, but sometimes of white mica or tremolite, and nodules made up of mafic material.

Nodules of almost pure diopside are common within the marble. They consist almost entirely of large interlocking crystals of diopside up to 2 mm across, with minor amounts of dolomite, olivine, chlorite and white mica, usually at the triple junctions between crystals. The crystals are anhedral, but triple junctions between them occur at approximately 120° (plate 6.6.A). The most common alteration is at the intersection of three crystals, where patches of calcite and serpentine occur. The serpentine occurs as long acicular crystals within a fine grained mass of calcite. Grains of dolomite are often altered to calcite at pyroxene boundaries. Rare cracks across the pyroxene are normally filled by calcite, but are occasionally filled by tremolite. Further alteration of the nodules, such as in SN. 27, leads to the replacement of diopside by amphibole. At first the amphibole occurs as small euhedral crystals at pyroxene rims but where pyroxene is more fully replaced, amphibole pseudomorphs the pyroxene, often with many inclusions of calcite (plate 6.6.B).

Diopside nodules also occur as much more fine grained rocks, composed of small polygonal crystals up to 0.5 mm across. The usual alteration of these rocks is to amphibole and ilmenite, with alteration of pyroxene at grain boundaries to form rounded pyroxene relicts in pools of amphibole and ilmenite. The amphibole is pleochroic from blue green to pale olive green to lavender blue. Larger anhedral inclusion free crystals of amphibole also occur. These are often strained, or else consist of patches of polygonal amphibole. Garnet also occurs, either as rims to rounded pyroxenes in a similar fashion to the amphibole , or in one sample, SN. 312, as large anhedral inclusion free crystals (plate 6.3.B). In this sample an unusual symplectite of garnet and pyroxene also occurs, with a rind of green amphibole between it and the polygonal pyroxene. In SN. 311, pale pink sphene occurs as small rounded crystals throughout the rock. In SN. 313 the occurrence of garnet around pyroxene grains is often restricted to narrow strips (plate 6.3.C), although a few rare larger garnets do occur. This latter sample is also cut across by cracks filled with epidote, calcite and tremolite, with no alteration at the rims of the cracks.

SN.'s 203 and 204 are from just north of Glen Beag (at GR 847167), very close to the locality described by Sanders (1978) as an Al - Ti - pyroxenite. SN. 203 is similar to SN. 311 - 313, described above. It consists of green amphibole with small amounts of sphene. The amphibole occurs as small anhedral crystals with a good cleavage and is weakly pleochroic from yellow green to pale olive green to bluish green. Rare large anhedral crystals of amphibole occur, with common fine grained pyroxene inclusions and rare calcite and white mica inclusions. The nodule gets more coarse grained to the rim, with an increase in the amount of pyroxene. This either occurs as small stubby crystals similar to the amphibole, or as large rounded crystals with many calcite inclusions. The marble at the nodule rim consists largely of calcite with crystals of pyroxene, amphibole, and white mica occurring between calcite grains, all with calcite inclusions. SN. 204 consists of pseudomorphs of large anhedral garnet and pyroxene. Pyroxene is far more common, and is replaced by a fine symplectite of either pyroxene and plagioclase or of amphibole and quartz. Garnet is replaced by epidote and white amphibole. Relicts of both garnet and pyroxene occur. Small crystals of sphene and calcite occur throughout. Part of the nodule consists entirely of large anhedral crystals of white amphibole, with small inclusions of white mica, pyroxene and garnet, or of calcite and zoisite (plate 6.6.D).

SN. 120 is a similar nodule with relicts of garnet and pyroxene. Pyroxene is altered in a similar manner to that of SN. 204, but the garnet is altered either to calcite and epidote, or to symplectites of epidote and scapolite (plate 6.3.D). SN. 262 comes from the same locality as SN. 311 - 313, near to the bimineralic eclogite of Lochan na Beinne Faide. Most of the rock consists of small anhedral pyroxenes in a matrix of garnet, tremolite, epidote and white mica. Rare large anhedral grains of strained pyroxene occur. Garnet occurs as small irregular grains full of tiny pyroxene crystals. White mica and tremolite occur in patches together. Epidote occurs throughout. The nodule is altered along cracks to pale green amphibole, epidote and calcite. The epidote occurs as small subhedral crystals within and at the boundaries of large anhedral amphibole and calcite. Parts of the nodule are altered to a coarse grained amphibolite with small inclusions of pyroxene, epidote, calcite and sphene (plate 6.6.C).

Less common than the diopside nodules are white mica - dolomite nodules. These also occur either as coarse grained or fine grained rocks. SN. 46 consists of large sheets of white mica up to 2 cm across with small inclusions of dolomite. The rims of dolomite crystals are altered to serpentine. SN. 56 is a similar rock, but much more fine grained, consisting approximately 80 % aggregates of white mica up to 1 mm across, with fine grained dolomite crystals and occasional chlorite between.

All of the above nodules contain largely Ca - Mg minerals and could well have been derived from segregation of the marble, although SN. 311 - 313 could possibly be derived from ultrabasic materials. However, a number of nodules from the marble, particularly at Lochan na Beinne Faide, have eclogitic affinities. Their field occurrence was briefly described in section 3.2 above.

Two nodules, SN.'s 259 and 260, are similar to each other, and occur approximately 2 m apart within the marble. SN. 260 has been folded. These nodules contain a wide variety of minerals including garnet, clinopyroxene, orthopyroxene, and QFK streaks (plate 6.4.A). Garnet is of variable size, occurring as both large anhedral crystals up to 5 mm across, and more commonly as small subhedral crystals. Rare inclusions of K - feldspar, quartz and clinopyroxene occur. Orthopyroxene also occurs as either large anhedral crystals or as small interlocking polygons. The large crystals are usually inclusion free. They are commonly strained, and sometimes have exsolution lamellae of clinopyroxene. Crystals of clinopyroxene are smaller, occurring as rare anhedral crystals or more rarely as interlocking polygonal grains. Quartz occurs throughout, between the larger anhedral grains, and ilmenite is common, usually between large garnet crystals. All of the above minerals are separated from each other by plagioclase, with the exception of rare garnet and ilmenite, and of orthopyroxene and clinopyroxene. This plagioclase is in optical continuity around many crystals. Crystals of the same mineral occur without plagioclase between. Garnet is altered to fine grained symplectites of either brown biotite and plagioclase, or of ilmenite and plagioclase. Clinopyroxene is always at least partly altered to a symplectite of ilmenite, diopside and plagioclase. Often this alteration occurs at the cores of crystals. Orthopyroxene generally remains unaltered. The QFK streaks are quartz and plagioclase poor, consisting mainly of polygonal K - feldspar with short stubby kyanite crystals between. Rare crystals of greenish biotite, of small subhedral garnet, and of polygonal clinopyroxene also occur within the streaks. QFK streaks are segregated into feldspar - kyanite portions and quartz (- clinopyroxene) patches (plate 6.7.A) in which quartz occurs as large clean, strained, anhedral crystals, sometimes with inclusions of clinopyroxene, which remains unaltered. Thin rinds of clinopyroxene are common between plagioclase and quartz at vein rims, often with a semi - continuous chain of ilmenite behind the plagioclase (plate 6.7.B). Both nodules are layered into garnet and clinopyroxene rich patches with orthopyroxene occurring in both.

SN. 263 consists mainly of large, elongate, anhedral crystals of clinopyroxene, often up to 1.2 cm long, separated by garnets up to 0.6 cm across, that are of variable shape and appear to fill the available space between large pyroxenes. This garnet is often partly recrystallised to aggregates of garnet up to 2 mm across with sutured edges. Between the garnet and the pyroxene are aggregates of either very fine polygonal clinopyroxene, or of garnet and calcite (plate 6.4.B). The large pyroxenes have patches rich in small sphene inclusions, normally towards the cores of crystals. The edges of the crystals tend to be messy with increasing proportions of calcite. Most of the interstitial material is garnet, riddled with small inclusions of pyroxene and calcite. Thin rinds of calcite commonly occur between garnet and pyroxene. Rare anhedral crystals of calcite occur, sometimes with rims of green amphibole. Rare apatite crystals occur with many tiny pyroxene inclusions (plate 6.7.C). This rock is similar to the Al - Ti pyroxenite of Sanders (1978), although with the additional presence of calcite.

SN. 261 consists of garnet, biotite, amphibole, pyroxene, quartz and feldspar (plate 6.7.D). The garnet occurs as large anhedral inclusion free crystals up to 2 mm across, with green amphibole and red biotite occurring at the rims. Pyroxene is rare, but occurs as anhedral crystals up to 1 mm across. The amphibole often occurs as small interlocking polygons. The quartz and feldspar both occur as fine grained, interlocking polygonal crystals. Between these minerals and the marble is a rind up to 4 mm across consisting of fine - grained, polygonal, yellow - green amphibole. Rare anhedral pyroxene and patches of epidote occur within this amphibole. The amphibole passes into coarser grained polygonal diopside up to 5 mm across, which then passes into coarse grained anhedral diopside with occasional sphene and calcite, similar to the diopside nodules described above.

Calc - silicate nodules also occur, distinguishable by their rusty weathering in the field. These nodules are usually large, with extreme mineralogical variation within them. Two end - member types can be distinguished, although most samples have patches of both types. One type, the more common, consists mainly of quartz and feldspar with variable proportions of white mica, zoisite, white amphibole and ilmenite. Quartz and feldspar tend to occur as large strained anhedral crystals, with irregular embayed grain margins. Zoisite is common, usually occurring as aggregates of fine grained crystals, generally along with flakes of white mica. Ilmenite is common throughout. The zoisite and white mica often occur in layers which define a weak fabric, which in one sample, SN. 71, is folded. The second type consist primarily of garnet and clinopyroxene. In SN. 72 garnet occurs as aggregates of fine grained rounded crystals, separated by Fe oxide, sphene and zoisite. Pyroxene is almost all altered to a fine grained symplectite with plagioclase, although rare relicts occur (plate 6.8.A). Small wisps of quartz and K - feldspar occur with the pyroxene. Large, anhedral, pale pink pleochroic sphene also occurs. The entire rock is cut by feldspar - zoisite - white amphibole veins.

6.4.3 Chemistry

The chemistry of the marbles was summarised by Rock (1987). All the marbles from Glenelg are pure dolostones. Only a couple of nodules were analysed by XRF. SN. 260 is very iron rich, with high Na, K, Si content.

The marbles are **calcite - dolomite** rocks with variable proportions of **olivine** and **diopside**. Alteration products of these latter two include **humite**, **biotite**, **chlorite**, **serpentine**, and **tremolite**, all of which are Mg - rich, Fe - poor. The olivine is almost pure forsterite and is most commonly altered to serpentine, but more rarely altered to humite, noted by Read and Double (1935), or chlorite. This latter contains some iron, with an Mg no. of about 0.95. Biotite also occurs, and has a similar Mg no.

The marble nodules can be divided into a number of groups; diopside nodules related to the marble; pyroxenites, similar to those described by Sanders (1978) elsewhere in the Eastern Lewisian; two pyroxene - garnet rock; and rocks bearing a resemblance to eclogites. All of these rocks are clinopyroxene bearing and most are garnet bearing. Amphibole is rare, but is never - the - less the most common alteration product.

Garnet occurs as two broad types, Fe rich with only 10% grossular and 20% pyrope, in one relict eclogite, and in the Fe - rich orthopyroxene - bearing nodules. The other type are Ca - rich with 60 - 70% grossular. These are plotted in figure 6.3.

Clinopyroxene from diopside nodules is, obviously, diopside with only small amounts of jadeite and tschermakite, with no aegerine. Pyroxene from other nodule types is variable, with individual nodules often having different compositions despite

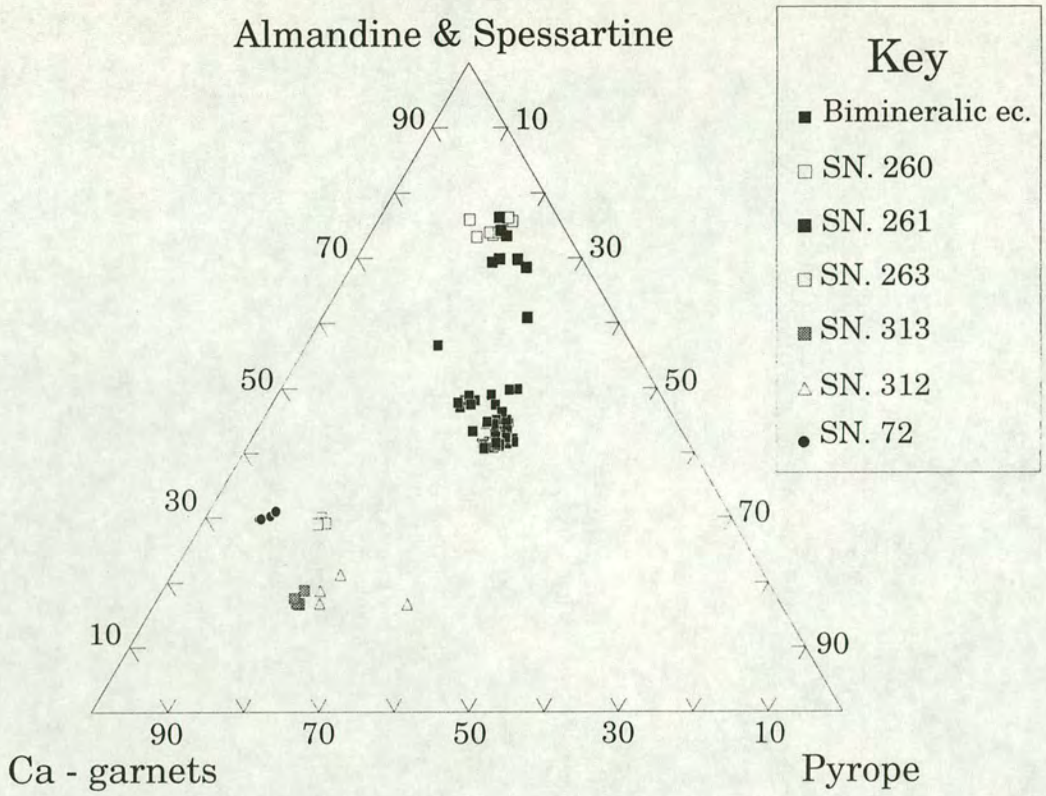


Figure 6.3 End member plot for garnets from Eastern Lewisian marble nodules. Garnets from SN.'s 260 and 261 are Fe rich, similar to garnets from the metapelites, although SN. 261 was apparently an eclogite. Garnets from other samples within marble nodules are Ca rich, whether from pyroxeneites (SN.'s 312, 313) or from altered eclogites (SN.'s 72, 263).

having similar textures. On the whole, those rocks that appear to have been eclogites contain pyroxene with up to 20% jadeite and often greater than 10% aegerine, more than is usual in the eclogites. These rocks show similar trends to eclogite pyroxenes with jadeite - rich, coarse crystals and jadeite - poor pyroxene coexisting with amphibole or plagioclase in fine grained symplectites. SN. 263 shows similar clinopyroxene chemistry to those described by Sanders (1978), being roughly of composition $(Na_{0.15}Ca_{0.85})[(Mg,Fe'')_{0.75}(Fe'''TiAl)_{0.25}](Si_{1.9}Al_{0.1})O_6$. The pyroxenites SN. 311 - 313 are Na poor, but in SN. 313 there are Al - Ti rich rims and Al - Ti poor cores. SN. 312 has all Al - Ti poor compositions, roughly $Ca_2[Mg_{0.85}(Fe'''TiAl)_{0.15}](Si_{1.85}Al_{0.15})O_6$. These are fassaites, high in Tschermak's molecule, similar to those described by Tilley (1938b). In SN. 260 the compositions are extremely variable from jadeite rich, tschermak free cores to jadeite poor rims. Clinopyroxenes occurring as inclusions within both garnet and orthopyroxene are the most jadeite rich. Clinopyroxene chemistry is summarised in figures 6.4. and 6.5.

Amphibole is not common, but does occur in diopside nodules and in pyroxenites, SN.'s 203, 204, and 311 - 313, probably replacing clinopyroxene. In diopside nodules the amphibole is almost pure tremolite. It also occurs in SN. 261, an altered eclogite, and SN. 263, similar to Sanders' (1978) pyroxenite. Amphibole from SN. 261 is pargasitic, of roughly $(Na,K)Ca_2([MgFe(tot)]_4Al)(Si_6Al_2)O_{22}(OH)_2$. The Mg no. is variable, from about 0.35 - 0.4 in amphibole occurring with diopside at the rim of the nodule, to about 0.65 at the centre of the nodule. Amphibole in SN. 263 is of composition $(Na,K)(Ca_{1.85}Mg_{0.15})([MgFe(tot)]_{3.85}Ti_{0.15}Al)(Si_6Al_2)O_{22}(OH)_2$. It has up to 1.2 wt % TiO_2, and lies between pargasite and grunerite, having less than 2 Ca per formula unit. Amphibole from the pyroxenites is variable, with higher Al content and no K in amphiboles occurring around garnets rather than pyroxenes. The amphiboles around pyroxenes are ferropargasites, similar to those in SN. 261, but with some Fe'''. Those amphiboles around garnet are of composition $NaCa_2([MgFe'']_{3.5}[AlFe''']_{1.5})(Si_{5.5}Al_{2.5})O_{22}(OH)_2$.

Other minerals include **orthopyroxene**, from orthopyroxene - bearing nodules (SN.'s 259, 260), which is Fe - rich, with only 45% enstatite (compared to approximately 75% in orthopyroxene - bearing eclogite); **scapolite** in SN. 120, an altered eclogite, of 30 - 40% meionite; '**epidote**' is always Fe''' poor, at almost the zoisite end member. **Phlogopite** occurs in some nodules, normally as almost pure Mg - end member. **Plagioclase** is rare, but occurs in calc - silicates as An_{23-27} (oligoclase), and within SN.'s 259, 260, orthopyroxene - nodules, and SN. 261, an altered eclogite, as An_{4-6} (albite). Al - rich, slightly pleochroic **sphene** occurs in some samples. In SN. 313 it is of composition $CaTi_{092}Al_{0.08}Si(O,OH)_5$, whilst in SN. 72 is extremely aluminous, $CaTi_{0.8}Al_{0.2}Si(O,OH)_5$

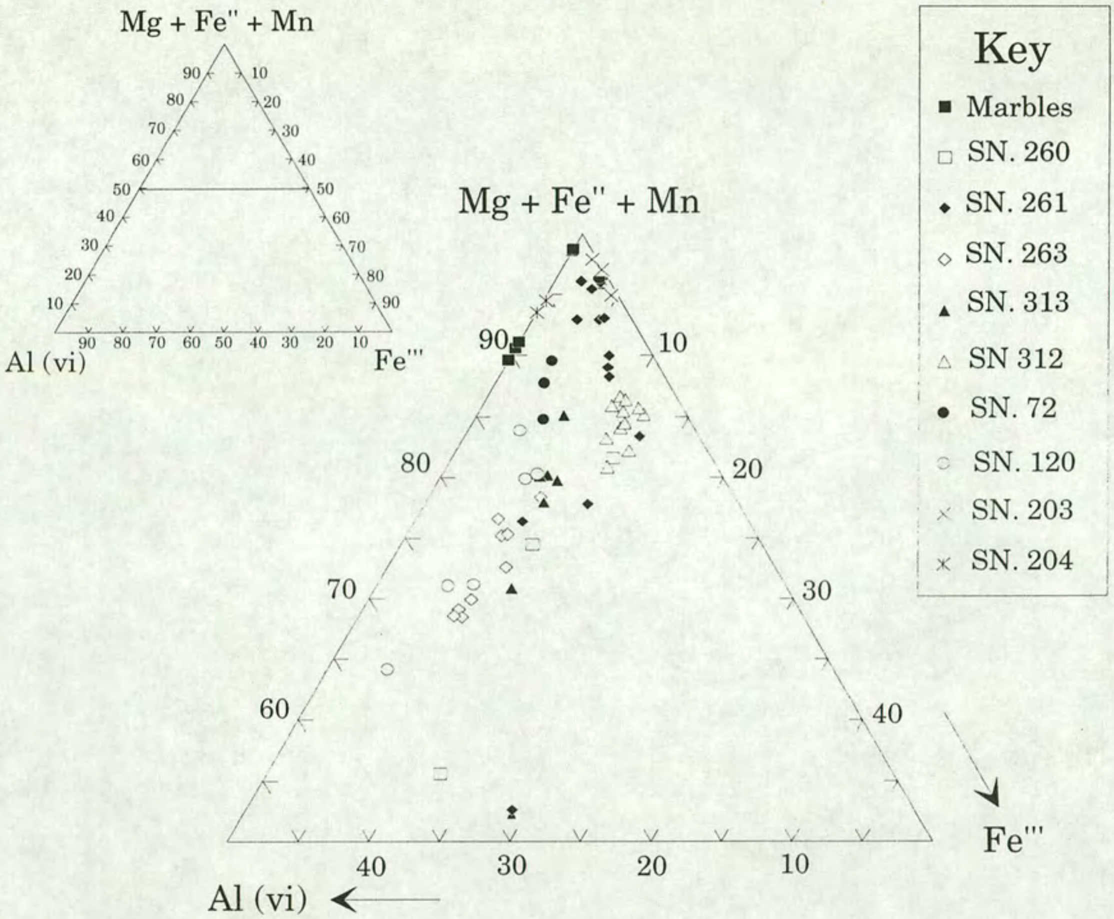


Figure 6.4 MMF - Al_{vi} - Fe''' plot for clinopyroxenes from Eastern Lewisian marbles and marble nodules. Pyroxenes from SN.'s 260, 261, 263 and 120 are relatively Al_{vi}, and hence jadeite, rich. Pyroxenes from SN's 312 and 313 are comparatively Fe''' rich.

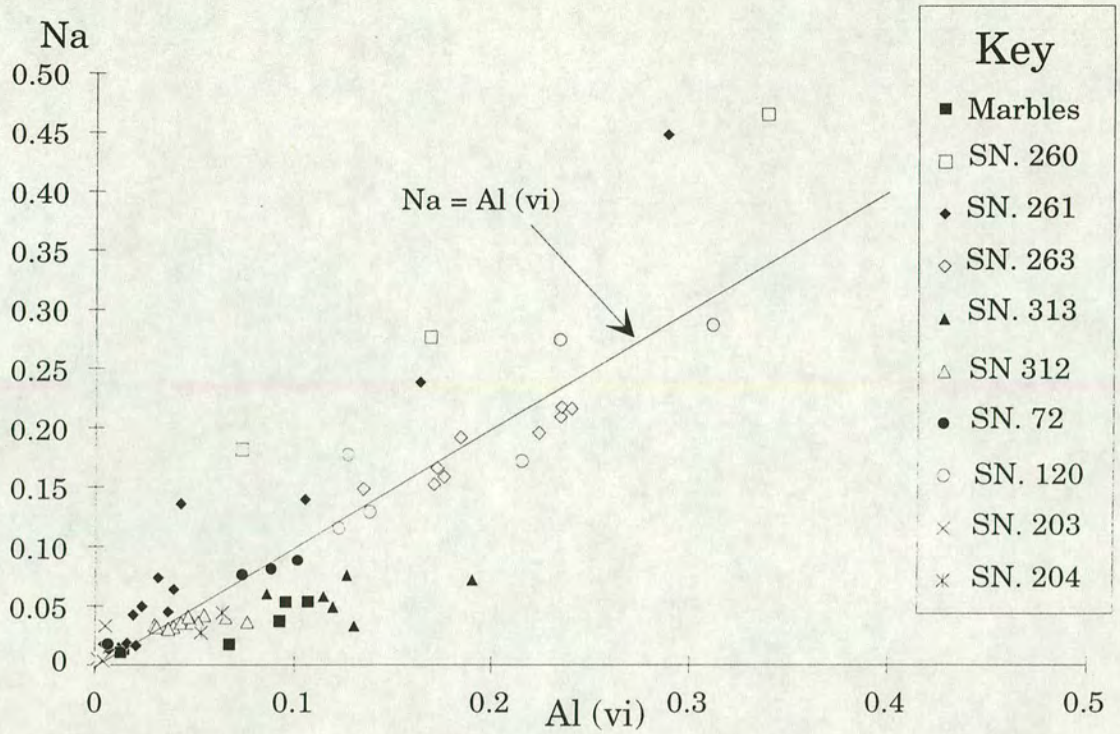


Figure 6.5 Na - Al_{vi} plot for clinopyroxenes from Eastern Lewisian marble nodules. Most samples either have Na ≈ Al_{vi} or Na > Al_{vi}. In the case of SN. 260 this is due to high aegerine content. However, SN.'s 312 & 313, in particular, contain much more Al_{vi} than Na and are Fassaitic.

6.4.4 Summary

The marbles themselves occur as coarse grained interlocking crystals with a high - grade mineralogy and give little hint as to the history of the area. Rock (1987) compared marbles from throughout the Lewisian inliers and the foreland, and showed that the Glenelg marbles were similar to those from South Harris. The marble nodules, however, are extremely varied and show a wide variety of textures and compositions. Many of these nodules occur due to the segregation of the marble into calcite and nodules of Ca - Mg silicates. Other nodules occur which definitely do not have a marble origin and which must have been either intruded into the marble or else tectonically emplaced. It is the textures in these nodules that are important in understanding both the history of the marble and that of the Eastern Lewisian.

The diopside and white mica nodules, probably derived from the marble, occur both as coarse anhedral crystals and as fine grained interlocking polygonal crystals. Alteration of the diopside nodules occurs with hydration to produce amphibole. Alteration of olivine in the marble also occurs through hydration. The common occurrence of retrograde hydrous phases within the marble (humite, serpentine), in nodules (tremolite) and in cracks across the marble and nodules (tremolite) suggests that fluids within the marble after initial metamorphism were hydrous rather than CO_2 rich. Tremolite ($Ca_2Mg_5Si_8O_{22}(OH)_2$) fills cracks across the marble at Lochan na Beinne Faide that are of similar orientation to those filled by hornblende across the eclogites. It has been shown (section 5.3.4) that actinolite within cracks across the bimineralic eclogites has not reacted with the host eclogites outwith the cracks. The diopside nodules, and hence presumably the marbles that contain them, have a similar textural history to the eclogites, with coarse grained anhedral crystals replaced by coarse polygonal crystals prior to general retrogression that occurred with hydration. This implies that the diopside nodules grew during the first phase of high pressure metamorphism.

SN. 263 and SN.'s 311 - 313 are problematic because of their resemblance to a Ti - Al pyroxenite described by Sanders (1978), interpreted as being a high - pressure cumulate formed from an alkali - basaltic rock. Sanders analysed two samples from the same outcrop, both of which are pyroxenites with up to 20% tschermak's molecule, but that have reasonably high Na content and are not fassaitic. These clinopyroxenes have exsolved garnet of up to 45% grossular, and contain small quantities of calcite and amphibole, one sample contains abundant spinel. The samples described in this thesis are different in that they have Ca - rich garnet (in SN. 263) that often forms large crystals, although these do appear to envelope earlier pyroxenes (section 6.4.2). The similarity of textures and mineral chemistry between SN. 263 and Sanders rocks is remarkable, and although there is no spinel in the nodule, they are without doubt the same rock type. Sanders suggests that the presence of the Al - Ti - pyroxenite suggests isobaric cooling at pressures over 10 Kb, due to the presence of garnet ex - solution laminae (Harte and Gurney, 1975) and that the rock equilibrated with the eclogites at about 600 - 650°C, from garnet - pyroxene thermometry. Estimates given in chapter ten for the temperature of formation of SN. 263 are of about 755°C, similar to those of the eclogites and far higher than the temperatures estimated by Sanders (1978) for the pyroxenites, which themselves are similar temperatures to those estimated for the retrogression of the eclogites.

The occurrence of SN. 263 within the marble, and the occurrence of sodic pyroxene with exsolved rutile or sphene in many of the eclogites (suggesting original high Ti content within the clinopyroxene), particularly in orthopyroxene - eclogites (e.g. SN. 511, 233), and the occurrence of exsolved garnet in SN. 511, suggests that the formation of the pyroxenite was not unique, and that originally high (Al) - Ti pyroxenites may have been fairly widespread, and formed an integral part of the suite of basaltic rocks that formed the eclogites.

Although SN.'s 311 - 313 are superficially similar to SN. 263 and to the pyroxenite described by Sanders (1978), chemically they are slightly different, and resemble the fassaitic rocks described by Tilley (1938b), with approximately 25 wt % CaO, and low Si with very little Na, suggesting Tschermak's substitution.

Many of the mafic marble nodules appear to have recrystallised once enclosed in the marble, because they contain calcite, but still consist predominantly of garnet and clinopyroxene. SN. 261 has reacted to produce a rind of diopside and amphibole between the eclogite and the marble, but does not otherwise seem to have been altered, and the eclogitic garnet, clinopyroxene and quartz is preserved along with biotite - amphibole and plagioclase similar to eclogites outwith the marble, such as SN. E2. Many samples have been altered in a similar manner to eclogites outwith the marble, with garnet recrystallising to form aggregates pseudomorphing original larger anhedral crystals and clinopyroxene altered to a fine grained symplectite.

SN.'s 259 and 260 are odd, both because they are extremely Fe rich, yet different to the biotite - eclogite from Loch Duich, which is Fe - rich, and because they appear to be in complete disequilibrium. However, they display an overall textural history similar to that of the eclogites, with coarse anhedral crystals of garnet - clinopyroxene - orthopyroxene intruded by QFK streaks, and then recrystallised to interlocking polygonal crystals. Strong deformation, producing marked compositional layering, appears to be of D_0 age (by correlation with eclogite history) because the polygonal texture appears to overgrow it. The occurrence of plagioclase (of An_{4-6}) between all phases, suggests decompression, with albite growing from clinopyroxene and quartz. This must occur after the D_0 deformation as the plagioclase is in optical continuity around more than one mafic crystal. This agrees with the suggestions of Sanders (1988), that isothermal decompression followed the initial metamorphism of both host rock and QFK streaks. Folding of the nodule probably occurred when it was introduced into the marble, with the lineation produced at the contact between the nodule and the marble by movement between the two during later deformation. The occurrence of kyanite with K - feldspar and without anorthite rims is probably because of the lack of Ca within the rock (surprising in a marble nodule!), all the main phases being Fe - Mg rich, plagioclase being albite. The presence of K - feldspar and kyanite without muscovite suggests that the nodule has remained dry during its late history. The occurrence of clinopyroxene and ilmenite bordering the plagioclase rich portions of streaks, and clinopyroxene between quartz and plagioclase is odd and is not readily explained.

The above sequence implies that the nodules were separate from the marble until at least after the possible intrusion of QFK streaks. The late history of the marble, and the nodules, is superficially similar to that of the eclogites, with alteration of clinopyroxene to produce a fine grained symplectite, and with cracks across the rocks filled by pale amphibole corresponding to dark amphibole cracks in the eclogites, of D_2 age (chapter three). The nodules must have entered the marble by tectonic (rather than igneous) means, because of their wide variety and small extent. This is most likely to have occurred during D_0, given that the marble appears to have acted as a rigid body during syn - Moine deformation due to the presence of cracks at the peak of metamorphism (D_2).

Conditions of metamorphism are discussed in chapter ten, but in summary, they cover a wide range of temperatures. Constraints on pressure are poor. In general the nodules give temperatures up to a maximum of 756°C, and these highest temperatures probably represent eclogite facies metamorphism.

6.5 Ultrabasic rocks

6.5.1 Petrology

With the exception of a websterite pod, described in the field in chapter three above, most of the ultrabasic rocks in the Eastern Lewisian are now highly altered to serpentine - chlorite - amphibole rocks. The possibility that an orthopyroxene bearing eclogite (SN. 511) was in fact an ultrabasic rock was briefly discussed in section 4.2.3.

Pristine websterite is a bimineralic clinopyroxene - orthopyroxene rock with roughly equal proportions of each mineral (plate 6.8.B). Both are large colourless anhedral crystals up to 3 cm across. Cracks occur across both minerals, filled by either calcite or phlogopite. Phlogopite is usually present as small stubby crystals pleochroic from sandy yellow to almost colourless, forming up to 25 % of the rock. Further alteration within much of the pod is limited to thin rinds of white amphibole between the two pyroxenes and to cracks filled with white amphibole and calcite.

The rim of the websterite pod is extensively altered (plate 6.8.C). Commonly it alters to a white amphibole - green amphibole - talc rock. The white amphibole either occurs as radiating needles pseudomorphing anhedral pyroxene, often with relict pyroxene cores, or occurs as large anhedral crystals completely replacing pyroxene. Talc occurs in a similar manner. Pale green amphibole, pleochroic from yellow green to green to blue green occurs with phlogopite, whilst extremely rare garnet occurs at the rims of small patches of quartz and feldspar. These minerals are cut by two sets of cracks. One set is filled with white amphibole and white mica, the former with many inclusions of calcite and zoisite. A second set occurs, filled by calcite and white amphibole.

Later alteration occurs after the filling of these two sets of cracks. This leads to the formation of a fine grained symplectite of clinopyroxene and plagioclase. Phlogopite within, and at the rims, of pyroxenes often has a thin rind of plagioclase between it and firstly the pyroxene and then the symplectite. With further alteration a coarse symplectite of biotite and fine symplectite occurs. This contains patches of coarse grained zoisite and white mica.

The rim of the pod has been strongly deformed. It now consists of extremely fine grained biotite, hornblende and quartz - feldspar. The biotite and hornblende occur as elongate crystals and define a strong fabric, which does not have any lineation.

A variety of other ultrabasic rocks occur throughout the Eastern Lewisian. Each occurs as a single outcrop and contacts are not seen. All have altered either to chlorite - white amphibole - magnetite or to chlorite - serpentine - magnetite. Apatite is a reasonably common accessory. A few samples show relict minerals. SN. 222 contain rounded knots of chlorite and magnetite within serpentine. In SN. 133 relicts orthopyroxene and white mica alter to chlorite, calcite and white amphibole, all of which occur in a matrix of serpentine (plate 6.8.D). All these rocks are commonly cut by veins filled with calcite.

6.5.2 Chemistry

Fresh websterite contains ortho - and clino - pyroxene. **Orthopyroxene** is about 85% enstatite, **clinopyroxene** is Mg - rich diopside with a minor jadeite component. **Biotite** within the websterite has an Mg no. of about 0.85. Rare amphibole has an Mg no. of about 0.9. Fresh websterite is rare and much of it has been altered to hydrous assemblages of amphibole - biotite - epidote, with clinopyroxene, dolomite and plagioclase. **Amphibole** is of variable composition. Both Mg no. and Si content change with retrogression. Fresh amphibole is Mg rich, with a Mg no. of about 0.85, and with nearly 8 Si per 23 oxygens. More altered rocks contain amphibole with a Mg no. of about 0.75 and under 7 Si per 23 oxygens. **Epidote** contains about 0.6 Fe''' in the Y site. Biotite in altered ultrabasic rocks has an Mg no. of about 0.78. **Plagioclase** occurs with the breakdown of clinopyroxene and is of composition An_{15-20} (oligoclase). Other more retrogressed rocks are **Mg - chlorite** rich with **serpentine**, **calcite** and **magnetite**.

6.5.3 Summary

The websterite shows similar features to the eclogites. It is first partly hydrated to form a three phase ortho - and clino - pyroxene, phlogopite rock. It is then more heavily altered to amphibole and talc prior to being cracked on two occasions. The rim of the pod consists of strongly deformed material that probably formed at the same time as cracking in the pod. Plagioclase rims also occur around some minerals, especially phlogopite. Other pods show evidence of both coarse grained anhedral crystals and of interlocking polygonal crystals. Relict websterite minerals are rare in other pods, most relicts are of white amphibole. Original pyroxenite seems to have altered firstly to chlorite - white amphibole rock, which then later to chlorite - serpentine rock. SN. 222 is interesting because large knots of chlorite and magnetite suggest the original presence of coarse rounded garnets, which must therefore have occurred in some ultrabasic rocks. Why the alteration of garnet bearing ultrabasic rocks should be any different to that of SN. 223, a garnet - two pyroxene rock described in section 4.3.2. above, is not clear.

6.6 Quartzo - feldspathic rocks

Quartzo - feldspathic rocks occur sporadically throughout the Eastern Lewisian. Generally they are pink, fine - grained rocks with a weak cleavage outlined by oriented micas. In thin section, many of the rocks, such as SN. 90, are seen to consist mainly of quartz, K - feldspar and plagioclase, with some biotite, muscovite and epidote. Quartzo - feldspathic material comprises up to 80% of the rock, with quartz and plagioclase far more common that K - feldspar, with epidote being the most common accessory phase. The rocks are mostly fine grained, with crystals up to a maximum of 0.5 mm across, although rare larger, strained crystals of quartz, plagioclase and K - feldspar occur up to 1 mm across. The micas are generally aligned parallel to one another, whilst tiny rounded epidotes occur in strings. Rare samples, e.g. SN. 233, contain rounded, colourless garnet, up to 3 mm across and either relict kyanite or margarite and zoisite after kyanite, occurring patchily throughout the rock. Sanders (1989) presents garnet and clinopyroxene analyses from a so - called quartzo - feldspathic gneiss, but no clinopyroxene has been found in these rocks, or is reported in either Peach *et al.* (1910) or May *et al.* (1993), and the clinopyroxene - bearing rocks mentioned by Sanders (1989) are thought to be similar to quartz - rich eclogites such as SN. 83, described in chapter 5.

The **plagioclase** is about An_{30} within the bulk of the rock. Garnet is of highly variable composition, with relatively Ca rich rims, $(Ca_{1.0}Mg_{0.6}Fe''_{1.3}Mn_{0.2})(Fe'''_{0.1}Al_{1.9})Si_3O_{12}$ and Ca poor cores, $(Ca_{0.6}Mg_{0.6}Fe''_{1.5}Mn_{0.2})(Fe'''_{0.1}Al_{1.9})Si_3O_{12}$. **Biotite** is Ti poor, with large Al_{vi} content. **Muscovite** has a small Mg, Fe'' component. Other minerals such as **zoisite** approach ideal end member compositions.

Estimates of the pressure and temperature of formation from garnet - kyanite bearing rocks indicate conditions similar to those within the eclogites after QFK vein intrusion, with conditions of about 790°C, 17 Kb, using garnet - biotite pairs and garnet - anorthite - kyanite - quartz equilibria.

6.7 Amphibolites

A small number of basic and possibly ultrabasic rocks occur throughout the Eastern Lewisian that are apparently anomalous, mentioned in chapter three. These rocks can be divided into four groups, plagioclase - amphibole rocks with different textures to retrogressed eclogites and three sets of plagioclase - free rocks; quartz - amphibole rocks; quartz - free epidote - amphibole rocks; and "amphibolitites" consisting of virtually pure amphibole. All these rocks are rare and only a few specimens of the latter three types have been collected. The first type, plagioclase - amphibole rocks, has not been sampled, but are described by May *et al.* (1993) as being hornblende - plagioclase - biotite - epidote - quartz - sphene rocks. Two types occur, coarse grained rocks derived from either pyroxene granulite or else coarse amphibolite, and medium grained rocks with no evidence of a previous metamorphic history. It is the latter that are important, and although no cross - cutting relationships have been found, Barber (1968) and May *et al.* (1993) suggest that the rocks may represent dykes intruded into the Eastern Lewisian after eclogite facies metamorphism.

6.7.1 Quartz - bearing assemblages

In the present study, only one sample of quartz - bearing, plagioclase - free amphibolite has been identified, that being the boudinaged rock occurring within a road cutting alongside Loch Duich, SN. 310 (see section 3.5.3). This rock is an amphibole - quartz - epidote - rutile - apatite bearing rock. There is no sphene. Both the presence of rutile without sphene and the absence of plagioclase within amphibolites is odd.

The rock consists predominantly of dark green, inclusion - free amphibole, up to 1 cm across. Epidote occurs throughout as smaller subhedral crystals full of inclusions of quartz and, more rarely, amphibole. Quartz, rutile and apatite occur as interstitial crystals throughout.

The rock is quartz normative, SiO_2 and FeO rich, MgO, CaO and Na_2O poor relative to the bimineralic eclogites, but with similar Al_2O_3. However, it is fairly similar in composition to an eclogite described by Yoder and Tilley (1962), the analysis given in appendix III. **Amphibole** is pargasitic, of approximate general composition : $Na_{0.6}K_{0.1}Ca_{1.8}([Mg_{2.0}Mn_{0.1}Fe''_{1.6}][Fe'''_{0.5}Ti_{0.1}Al_{0.7}])(Si_{6.2}Al_{1.8})O_{23}(OH,etc)_2$. **Epidote** is close to end member compositions.

6.7.2 Quartz - free assemblages

Other rare rocks exist within the Eastern Lewisian that consist of amphibole - epidote - sphene, without quartz, feldspar, and neither ilmenite or rutile cores to sphene. These rocks are fairly coarse grained, with up to 50% amphibole, 35% epidote and 15% sphene. Inclusions of both epidote and sphene are common within the amphibole. In SN. 93, from north of Glen Beag, the dark green amphibole is partly altered to almost colourless actinolite around the rims of many crystals, similar to rare rocks seen within the Western Lewisian (chapter eight). These amphibole - epidote rocks are different to ultrabasic rocks because of the presence of both epidote and sphene, different to basic rocks because of the absence of quartz or feldspar.

The dark green **amphibole** is similar in composition to that from the eclogites, being of $K_{0.2}Na_{0.5}Ca_{1.9}([Mg_{1.9}Mn_{0.1}Fe''_{2.0}][Fe'''_{0.6}Ti_{0.1}Al_{0.3}])(Si_{6.5}Al_{1.5})O_{22}(OH)_2$. The secondary actinolite is of composition $Na_{0.1}Ca_{1.9}([Mg_{3.2}Mn_{0.1}Fe''_{1.4}][Fe'''_{0.2}Al_{0.1}])(Si_{7.8}Al_{0.2})O_{22}(OH)_2$. The **epidote** is Fe rich, the **sphene** Al poor.

6.7.3 "Amphibolitites"

In chapter three there were also described amphibolitites, particularly a few pods at Hazel Brae, that consisted of virtually pure amphibole, as interlocking crystals up to 1 cm across. Rare patches occur with quartz. The rocks pass into schistose amphibole - plagioclase - rutile rocks. The rock, e.g. SN. H6, is Cr rich, SiO_2 rich rock, in that respect similar to the orthopyroxene bearing rock found a few hundred metres away near to Fern Villa (chapter three), but otherwise distinctly Al_2O_3 and CaO poor, and FeO rich. It is, however, apart from SiO_2 content, broadly similar to the orthopyroxene - bearing eclogite described by O'Hara (1960) (the analysis given in appendix III) in respect to its relative proportions of Al_2O_3, CaO, MgO and FeO. Two compositions of amphibole occur. The most common, making up almost all the sample, are Si rich, of approximate composition : $K_{0.1}Na_{0.5}Ca_{1.8}([Mg_{3.1}Fe''_{1.0}][Fe'''_{0.5}Ti_{0.1}Al_{0.4}])(Si_{6.9}Al_{1.1})O_{22}(OH,etc)_2$. Rare Si poorer crystals occur with quartz : $K_{0.2}Na_{0.7}Ca_{1.8}([Mg_{2.5}Fe''_{1.3}][Fe'''_{0.6}Ti_{0.1}Al_{0.5}])(Si_{6.4}Al_{1.6})O_{22}(OH,etc)_2$. Both amphiboles have relatively high Cr content, up to 0.03 atoms per 23 oxygen.

6.7.4 Summary

There is some evidence to suggest that the above rocks may not have been metamorphosed at eclogite facies, as follows :

- Barber (1968) and May *et al.* (1993) describe metabasic plagioclase - amphibole bearing rocks with no evidence for the former presence of garnet (perhaps in the form of epidote - plagioclase - amphibole intergrowths) or clinopyroxene (in the form of sieved amphibole), and rutile is not described. Other basic rocks throughout the Eastern Lewisian all show some evidence of having been metamorphosed at eclogite facies by the presence of all or some of the above minerals and textures.

- Although it is possible that the rocks described above may be altered versions of eclogites or websterites, or even of the pyroxenites described by Sanders (1978) (the "amphibolitite" in particular is Cr rich, and does occur in close proximity to SN. 511, a two - pyroxene, garnet - bearing rock), in both chapters four and six respectively and in Sanders (1972) both basic and ultrabasic rocks are described as to hornblende - plagioclase or altering to hornblende - plagioclase - biotite - talc bearing assemblages respectively whilst the rocks described above consist of predominantly hornblende or actinolite.

- All the rocks in the Eastern Lewisian other than the possible dykes show evidence of having been initially metamorphosed under dry conditions, with almost exclusively anhydrous phases stable in basic and ultrabasic rocks, described above and by Sanders (1972). The possible dykes show no evidence of having had stable anhydrous phases, other than quartz or feldspar.

The implications of the rocks not having been metamorphosed to eclogite facies are that they were either intruded into the Lewisian after high pressure metamorphism, or are associated with the Moine. The latter is extremely unlikely as no dykes have been found within the Moine bounding the Lewisian at Glenelg, and it is therefore suggested that these rocks represent basic and ultrabasic dykes intruded into the Lewisian after high grade metamorphism, perhaps in a similar manner to the Scourie dykes of the foreland Lewisian.

The only definite proof that there were dykes intruded into the Eastern Lewisian would be if amphibolite facies dykes were seen cutting across QFK streaks within eclogites. So far this has not been seen in the field. Sanders (1972) suggested that there may have been dykes in the Eastern Lewisian because there were demonstrable dykes in the Western Lewisian, and suggested that the Eastern Lewisian eclogites may therefore represent metamorphosed dykes, although the assertions of Barber (1963) and May *et al.* (1993) and above cast doubt on this.

Whilst there is no actual concrete proof that the basic rocks described briefly above either occur with cross cutting relationships to the eclogites and related amphibolites, or that they never saw eclogite facies metamorphism, or that they are of different compositions to rocks within the bulk of the Eastern Lewisian, there is enough evidence to suggest that the rocks may well not have suffered the early history of other Eastern Lewisian rocks. Whilst this is only negative evidence, it is felt that the implications of the presence of possible dykes that have not seen eclogite facies metamorphism, along with the presence of less - disputed evidence of such dykes within the Western Lewisian casts doubt on the history of the rocks presented by Sanders *et al.* (1984), and is also enough to question the assertion of Sanders (1972) that any dykes that may occur were metamorphosed to eclogite facies.

No estimates for the pressure or temperature of metamorphism have been obtained for these rocks due to their restricted mineralogy.

6.8 Conclusions

With the exception of the basic rocks described in section 6.7 above, the non - mafic rocks from the Eastern Lewisian all have similar histories to the eclogites with a peak of metamorphism recorded after the widespread intrusion of QFK material forming streaks and pools in the rocks, although limited outcrop and occurrence limits the correlation of ultrabasic rocks and eulysites, and limited mineralogy, the marbles. In the metapelites and many marble nodules there is evidence for coarse grained crystals being recrystallised to finer grained, but still fairly coarse, polygonal intergrown crystals. The most interesting rocks are the nodules within the marble that are extremely varied and which have a wide variety of chemistries and textures. All of these have an early history that corresponds more or less to that of the rocks outwith the marble, although they appear to have been shielded by the marble from the effects of later deformation and retrogression. Thermometry (Sanders (1989), this thesis) and petrology suggests that rocks with QFK streaks were deformed and metamorphosed at about 750°C, and that they were subsequently enveloped within the marble. SN. 263 is similar to a cumulate described by Sanders (1972, 1978), thought to be an alkali - basalt, and constrains the formation of this type of rock to the early part of the areas history, probably prior to the formation of QFK streaks. The inference that most of the mafic rocks of Glenelg were derived from alkali - basalts (chapter five) suggests that the cumulate may be part of the overall broad suite of rocks represented by the Glenelg eclogites. SN.'s 259 and 260 are different to any of the rocks found outwith the marble and their origin is not known, but they have a similar history to all the other rocks, other than the presence of large quantities of albite around all the main phases in the rock.

As suggested in section 6.7.4 above, there is some basis for thinking that some basic and ultrabasic rocks within the Eastern Lewisian were intruded into the rocks of the Eastern Lewisian after eclogite facies metamorphism. The implications of this assertion are discussed in the conclusions (chapter eleven).

Plate 6.1.

A) Coarse garnet - biotite - quartz - feldspar rock (SN. 10). Garnet is cracked. The cracks are filled by biotite and plagioclase. (field of view : 14 mm).

B) Kyanite and biotite within a metapelite (SN. 8). (field of view : 6 mm).

C) "Garnetite" (SN. 271). Coarse garnet with minor rutile, quartz and biotite. Biotite forms symplectites with quartz. Some of the cracks across the garnet are filled by chlorite. (field of view : 15 mm).

D) Garnet - biotite - quartz - feldspar rock from Lochan na Beinne Faide (SN. 318). Subhedral, cracked garnet (pale, high relief) and clumps of fine grained biotite (dark). (field of view : 14 mm).

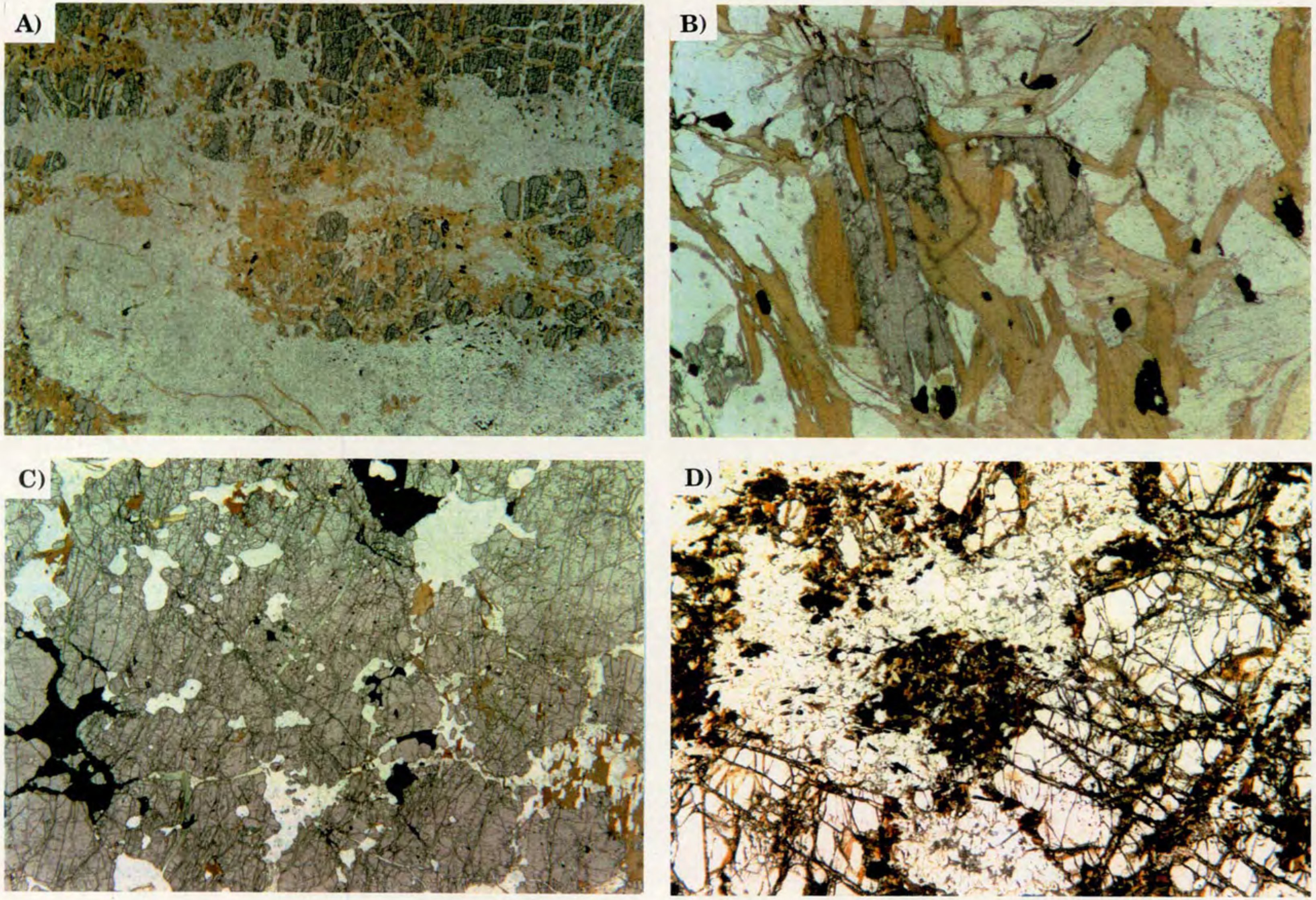

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Plate 6.2.

A) Garnet - quartz - feldspar rock from Lochan na Beinne Faide (SN. 315). Subhedral garnet (pale, high relief) with minor biotite and rutile (both dark). Quartz and feldspar both as anhedral crystals partly recrystallised to a finer polygonal groundmass. (field of view : 15 mm).

B) Garnet - biotite - quartz - feldspar rock with small rounded garnets, partly altered to biotite (SN. 98). Biotite and rare chlorite (green) outline a schistosity. (field of view : 14 mm).

C) Eulysite (SN. 95). Garnet (pink), clinopyroxene (paler green) and quartz. Garnet has inclusion free cores, and slightly darker inclusion (quartz) rich rims. Clinopyroxene is partly altered to amphibole (dark green). (field of view : 8 mm).

D) Retrogressed eulysite (SN. 223). Mostly interlocking polygonal amphibole, with rare apatite and garnet. (field of view : 17 mm).

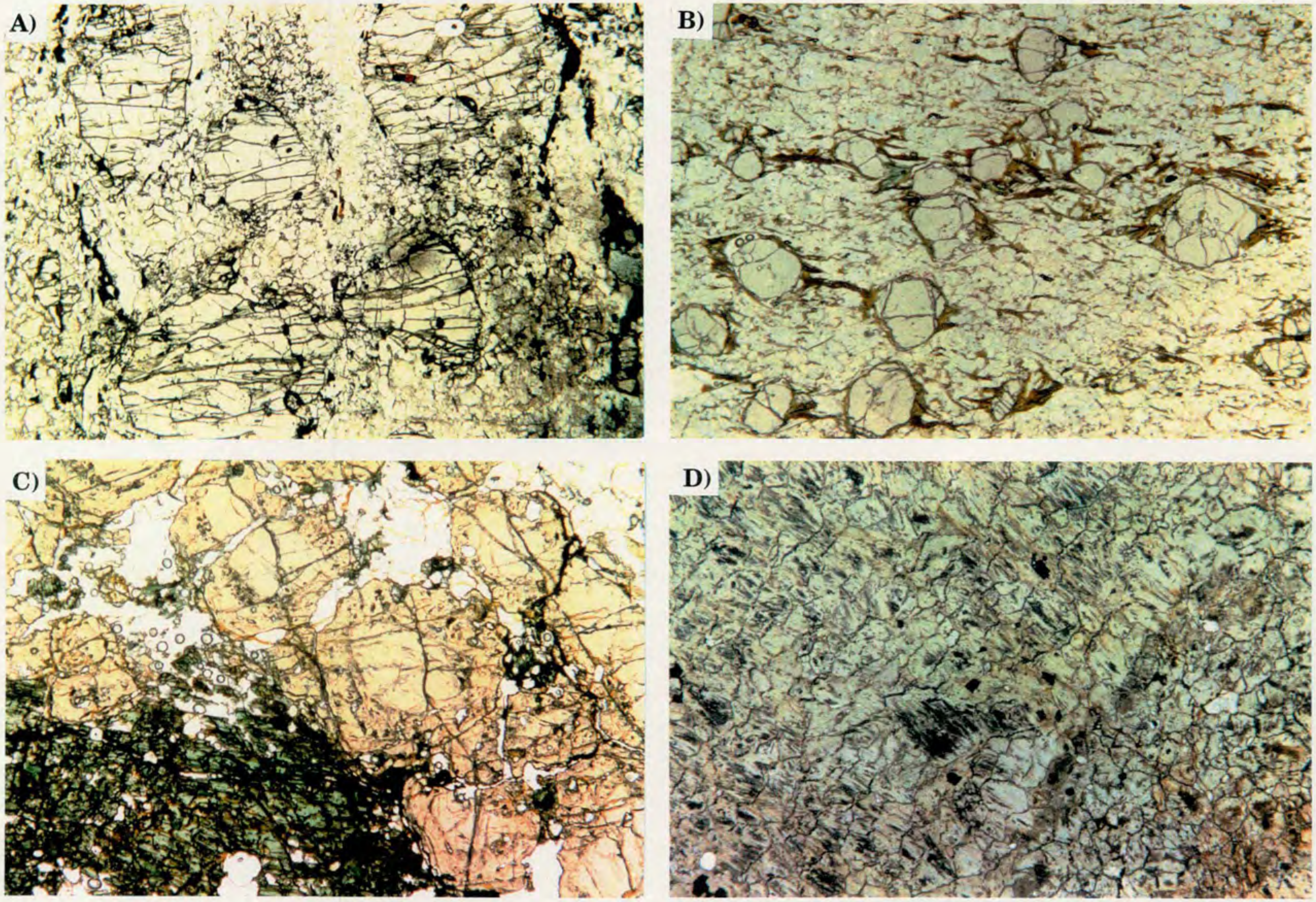
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Plate 6.3.

A) Olivine marble (SN. BH). Olivine (high relief) is altered either to serpentine along cracks or to humite (bright yellow), with diopside (clear) and calcite (dusty). (field of view : 10 mm).

B) Pyroxenite nodule (SN. 312). Polygonal clinopyroxene with ilmenite (black), amphibole (dusty) and garnet (pink). The bulk of the sample is as left, with pyroxene and small patches of amphibole and sphene. Large anhedral garnets are rare. (field of view : 20 mm).

C) Pyroxenite nodule (SN. 313). Polygonal clinopyroxene with sphene (brown), containing a band of anhedral garnet (running left - right near bottom) with inclusions of quartz. (field of view : 6 mm).

D) Eclogite nodule (SN. 120). Clinopyroxenes have altered to a fine grained symplectite of clinopyroxene and plagioclase (dusty). Garnets have altered to intergrowths of scapolite and zoisite (pale). Sphene occurs throughout (brown). (field of view : 15 mm).

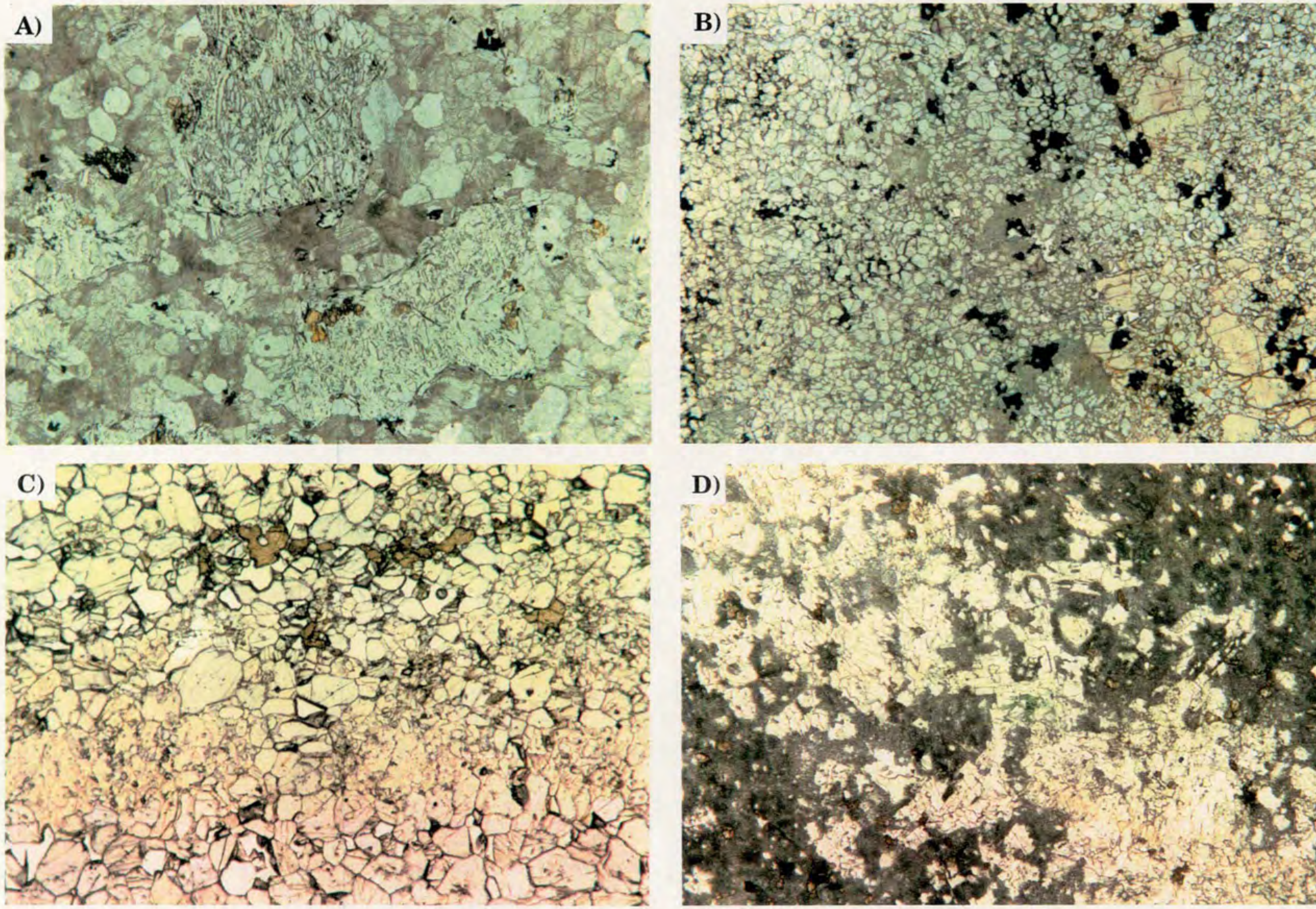
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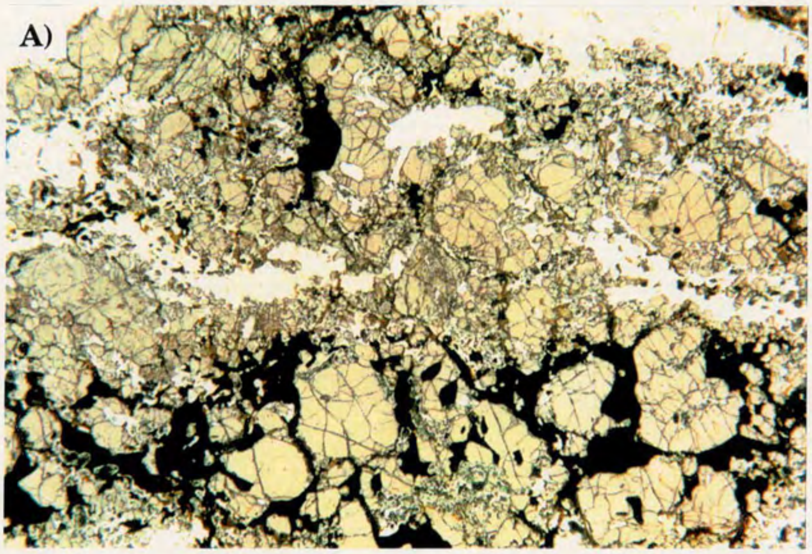
Plate 6.4.

A) Eclogite nodule (SN. 260). Garnet - orthopyroxene rich rock. Garnet (pink, rimmed by ilmenite) and orthopyroxene (pink) form the bulk of the rock. Small clinopyroxene crystals (green), and biotite (brown) occur. All minerals except garnet and ilmenite have rims of feldspar. (field of view : 7 mm).

B) Eclogite nodule (SN. 263). Coarse clinopyroxene (green) and garnet (pink). Clinopyroxene contains patches rich in sphene inclusions (brown streaks). Garnet tend to form an aggregate with calcite. (field of view : 19 mm).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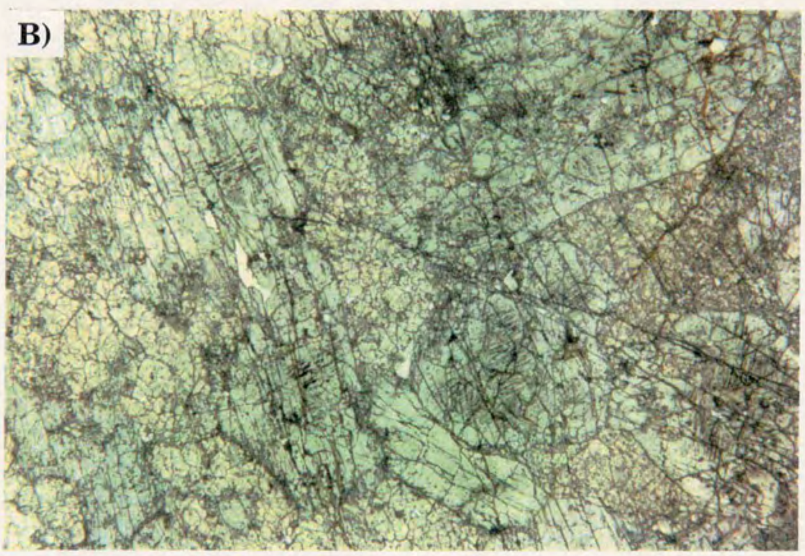
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Plate 6.5.

A) Segregated quartz (clear) and plagioclase - kyanite - ilmenite (dusty) (SN. 10A). Garnet in top left corner. (field of view : 3 mm).

B) Garnet - kyanite - biotite - quartz - feldspar rock (SN. 7). (field of view : 8 mm).

C) Folded biotite - quartz - feldspar rock (SN. 5). (field of view : 12 mm).

D) Retrogressed eulysite (SN. 94). Two amphiboles (dusty and pale) comprise the bulk of the rock. Also garnet and quartz. (field of view : 10 mm).

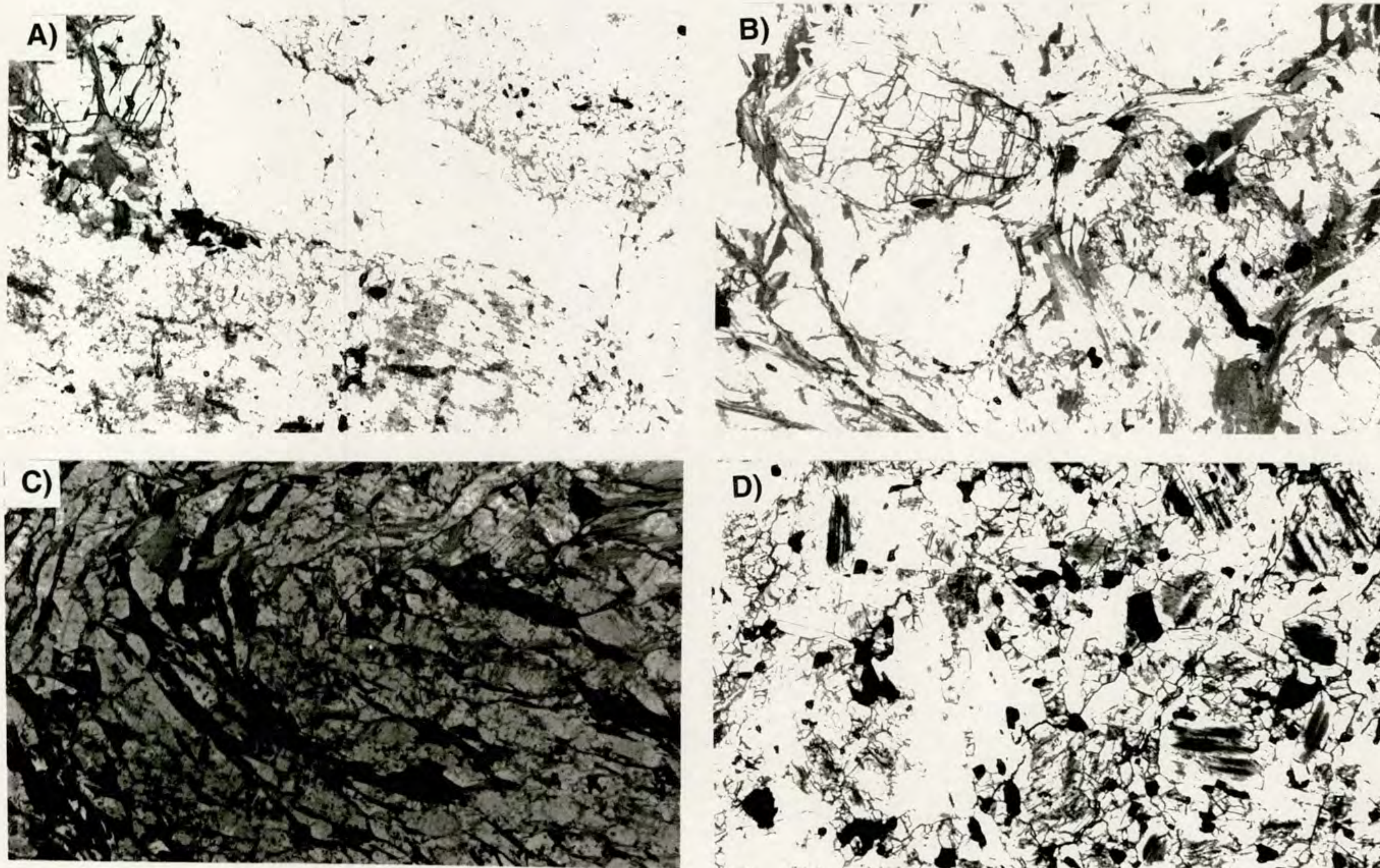
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Plate 6.6.

A) Diopside nodule in marble (SN. 56). Interlocking polygonal crystals of diopside. (field of view : 10 mm).

B) (in crossed - polars) Diopside nodule (SN. 27). Diopside (dark) is partly replaced by amphibole (pale). (field of view : 8 mm).

C) Eclogite nodule (SN. 262). Eclogite retrogressed to amphibolite. The bulk of the rock is comprised of amphibole (dusty) and epidote (clear) with relict garnet (high relief) and clinopyroxene (dark dusty). Cracks are filled with pale green amphibole. (field of view : 25 mm).

D) (in crossed - polars) Eclogite nodule (SN. 204). Interlocking white tremolite (dark, bottom left) and messy relict clinopyroxene - garnet (rest). (field of view : 10 mm).

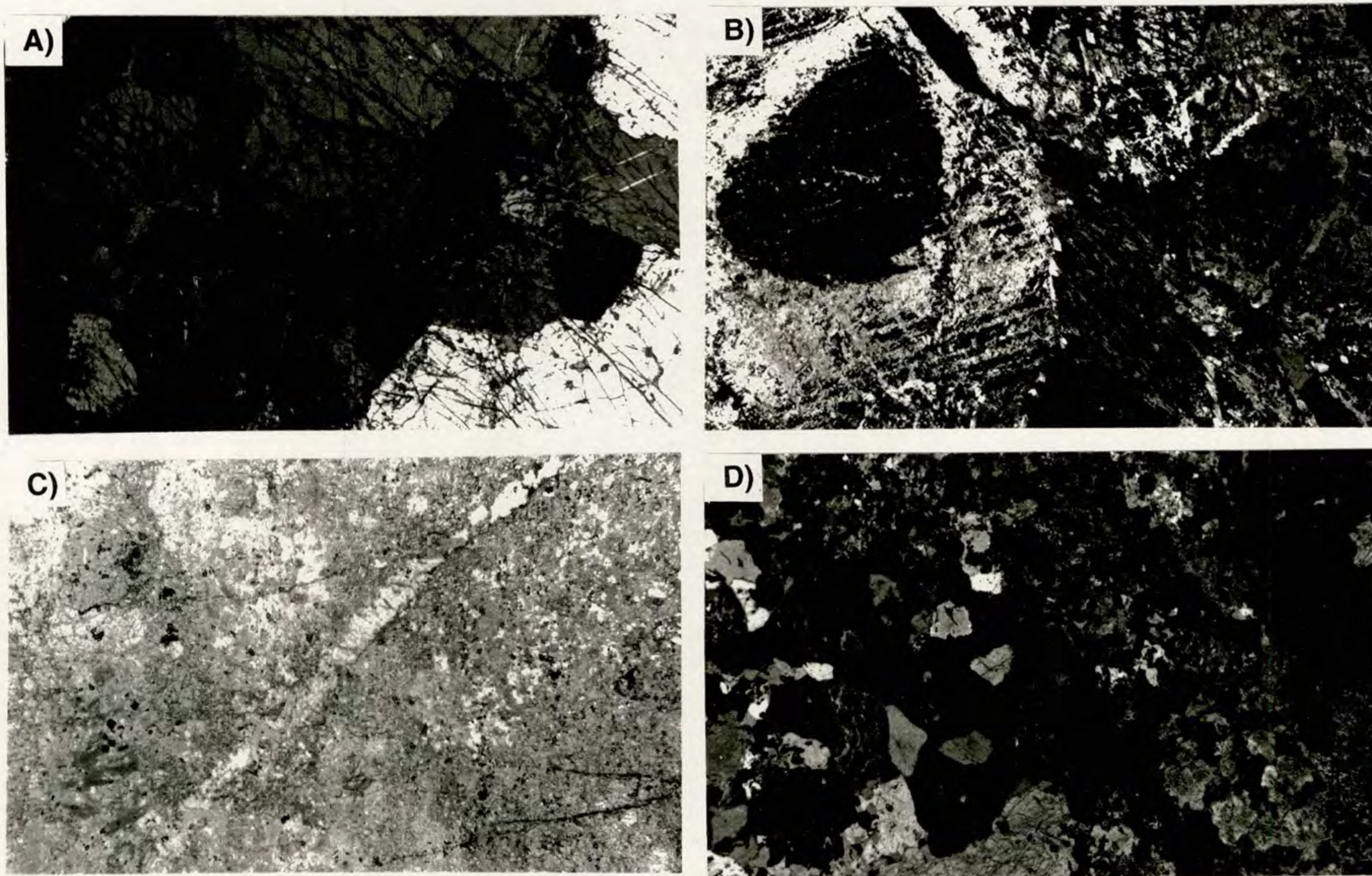
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Plate 6.7.

A) Eclogite nodule (SN. 260). Segregated quartz (clean) and plagioclase - clinopyroxene (slightly darker) within eclogite in which all minerals are separated by plagioclase. (see plate 6.4.A). (field of view : 5 mm).

B) Eclogite nodule (SN. 260). Quartz vein, rimmed by clinopyroxene, then plagioclase, then ilmenite (left) or by orthopyroxene (right). (field of view : 2 mm).

C) Eclogite nodule (SN. 263) Apatite crystals full of clinopyroxene inclusions. (see plate 6.4.B). (field of view : 2.5 mm).

D) Eclogite nodule (SN. 261). Diopside (pale, bottom) rims retrogressed eclogite that comprises amphibole (dark) and garnet (pale, high relief). Small eclogitic pyroxenes occur within the amphibole. (field of view : 14 mm).

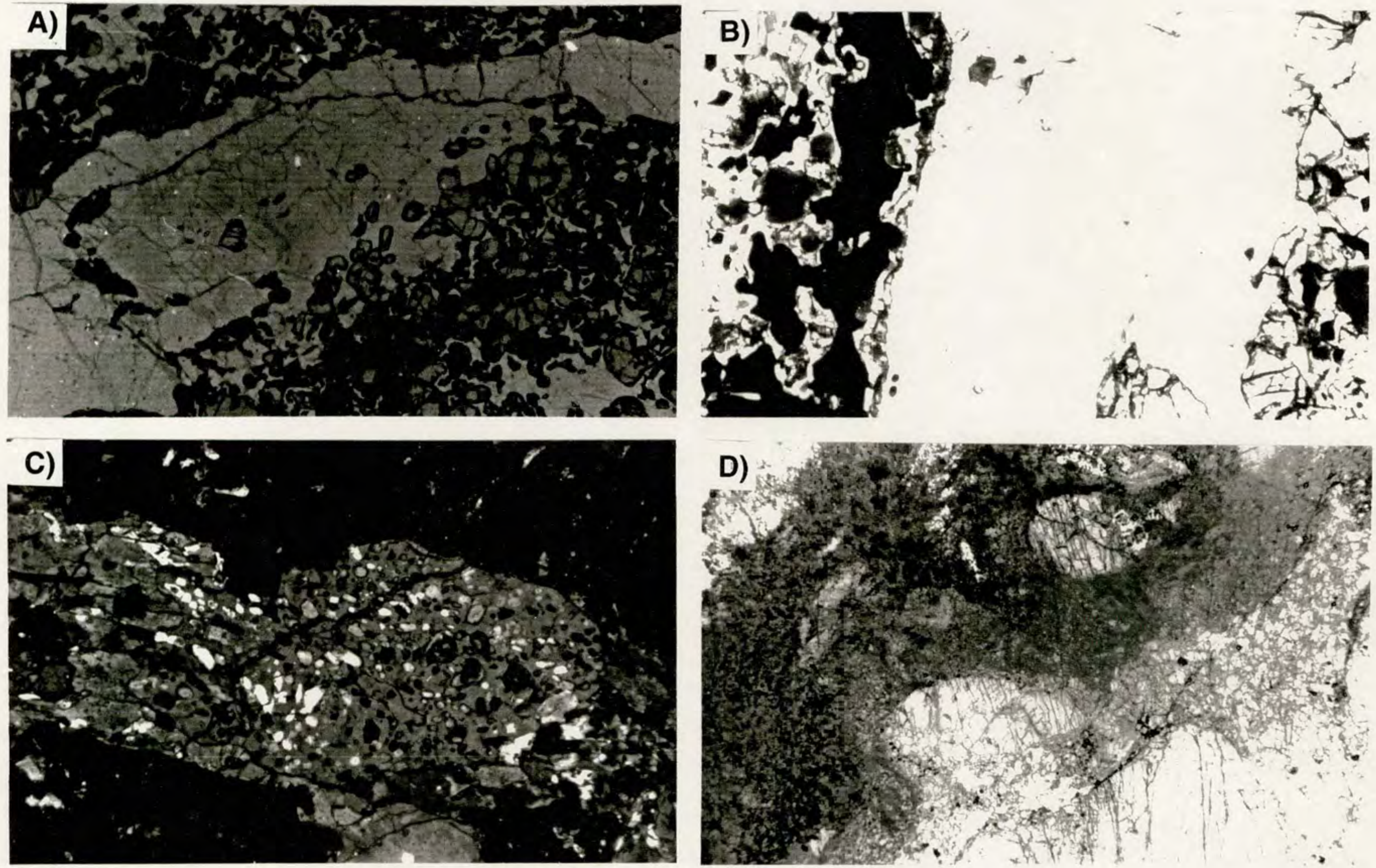
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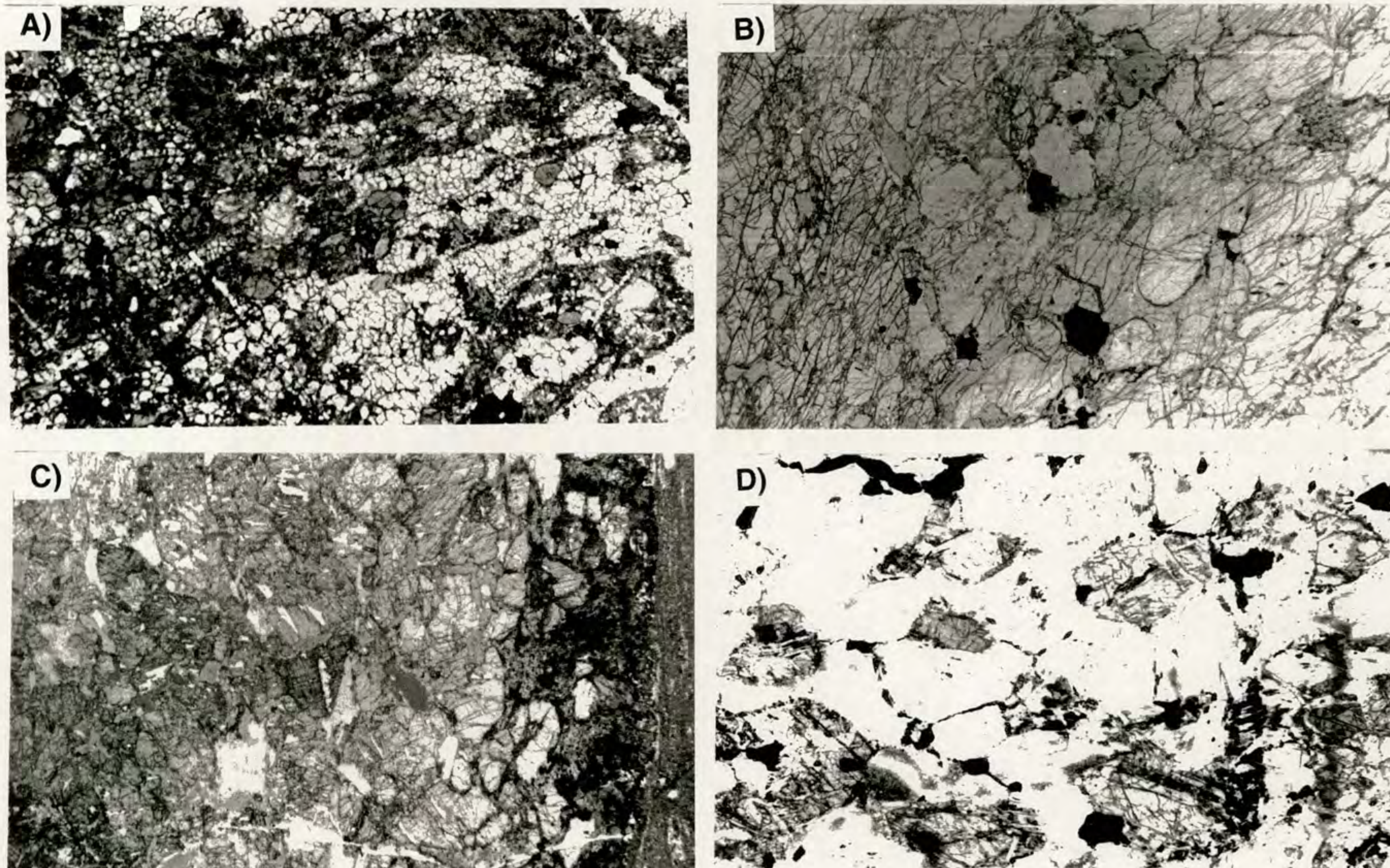
Plate 6.8.

A) Eclogite nodule (SN. 72). Garnet (pale high relief) and clinopyroxene (dark) with much sphene (dusty). All occur as clumps of fine grained interlocking crystals. Cut by plagioclase - calcite veins. (field of view : 22 mm).

B) Websterite (SN. 301). Rounded, interlocking orthopyroxene (pale) and clinopyroxene (dark), with ilmenite (black) and biotite (mid grey). (field of view : 11 mm).

C) Rim of websterite pod. Websterite (left) is altered to biotite and plagioclase (right) (SN. 302). The pod is bordered by extremely fine - grained biotite - amphibole - plagioclase - quartz (far right). (field of view : 30 mm).

D) Ultrabasic rock (SN. 133). Polygonal chlorite rimmed by iron oxide. Talc and amphibole (high relief) between. (field of view : 10 mm).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PART THREE
The Western Lewisian

Chapter Seven

Field description of the Western Lewisian rocks

CHAPTER 7

Field description of the Western Lewisian rocks

7.1 Introduction

In this chapter the field relationships of the Western Lewisian rocks are described and interpreted. Figure 7.1. shows the distribution of the Western Lewisian rocks at Glenelg. They occur in a strip up to 5 km wide and 25 km long extending from the south shore of Loch Carron to the north shore of Loch Hourn. Lewisian rocks found on the Sleat peninsula on Skye are almost certainly a continuation of this strip. The Western Lewisian is bounded by two continuous belts of Moine. That to the west rests unconformably upon the Western Lewisian, with a basal pelite and conglomerate at the contact (Peach *et al.*, 1910; Ramsay, 1957). The eastern belt of Moine is highly deformed and forms a narrow zone separating the Eastern and Western Lewisian. South of Loch Alsh, the Western Lewisian is separated into two strips by a thin sliver of Moine rocks. To the east of the Strathconon fault, which bounds the area to the SE, these relationships are repeated.

The rocks of the Western Lewisian are by no means as varied as those of the Eastern Lewisian, being devoid of recognisable metasediments. They consist of metamorphosed acidic, basic and ultrabasic igneous rocks. Descriptions of these rocks can be found in the Survey memoirs (Peach *et al.*, 1910; May *et al.*, 1993), Ramsay (1957) and in Barber and May (1975). Most of the Western Lewisian consists of strongly deformed amphibole - biotite - quartz - feldspar bearing rocks. These contain a variety of pods and bands of other, usually less deformed, rocks. Barber and May (1975) report relict pyroxene bearing granulite facies rocks north of Loch Alsh, and Sanders (1972) notes the occurrence of eclogite at Sandaig in the south of the area.

Almost all the fieldwork on the Western Lewisian in this thesis has been concentrated on the north coast of Loch Hourn where there is a complete section across the strike of the Western Lewisian rocks. This section stretches from GR 795117 at

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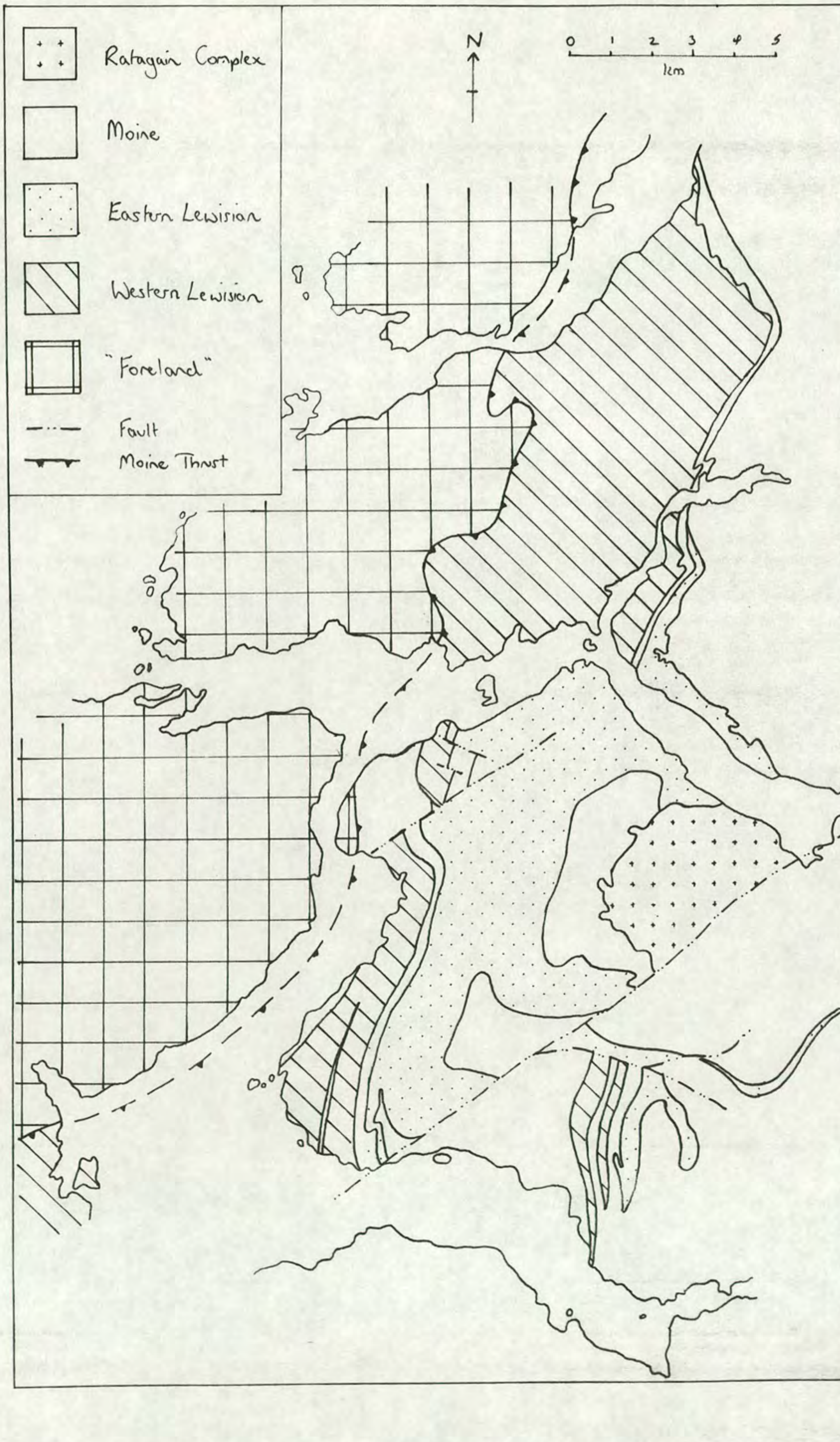
Figure 7.1 (following page) : Sketch map of the general geology of the Glenelg peninsular and surrounding area with the outcrop of Western Lewisian rocks highlighted.


Ratagain Complex
Moine
Eastern Lewisian
Western Lewisian
"Foreland"
Fault
Moine Thrust
N
0 1 2 3 4 5
km

Camas na Ceann in the east, to GR 769152, just north of Sandaig in the west, and generally consists of steep sloping, rocky outcrop in a strip some 5 - 10 m wide. The whole area south of the Glen More of Glenelg, including the Western Lewisian along the north coast of Loch Hourn, was mapped by Ramsay (1957). From east to west across the section there is a general change in the intensity of late (D_2 and D_3) deformation, leaving the rocks relatively undeformed by late deformation events in the east, but strongly deformed by these events in the west. This change was described by Ramsay (1957), and is illustrated in Figure 7.2, after Ramsay (1957).

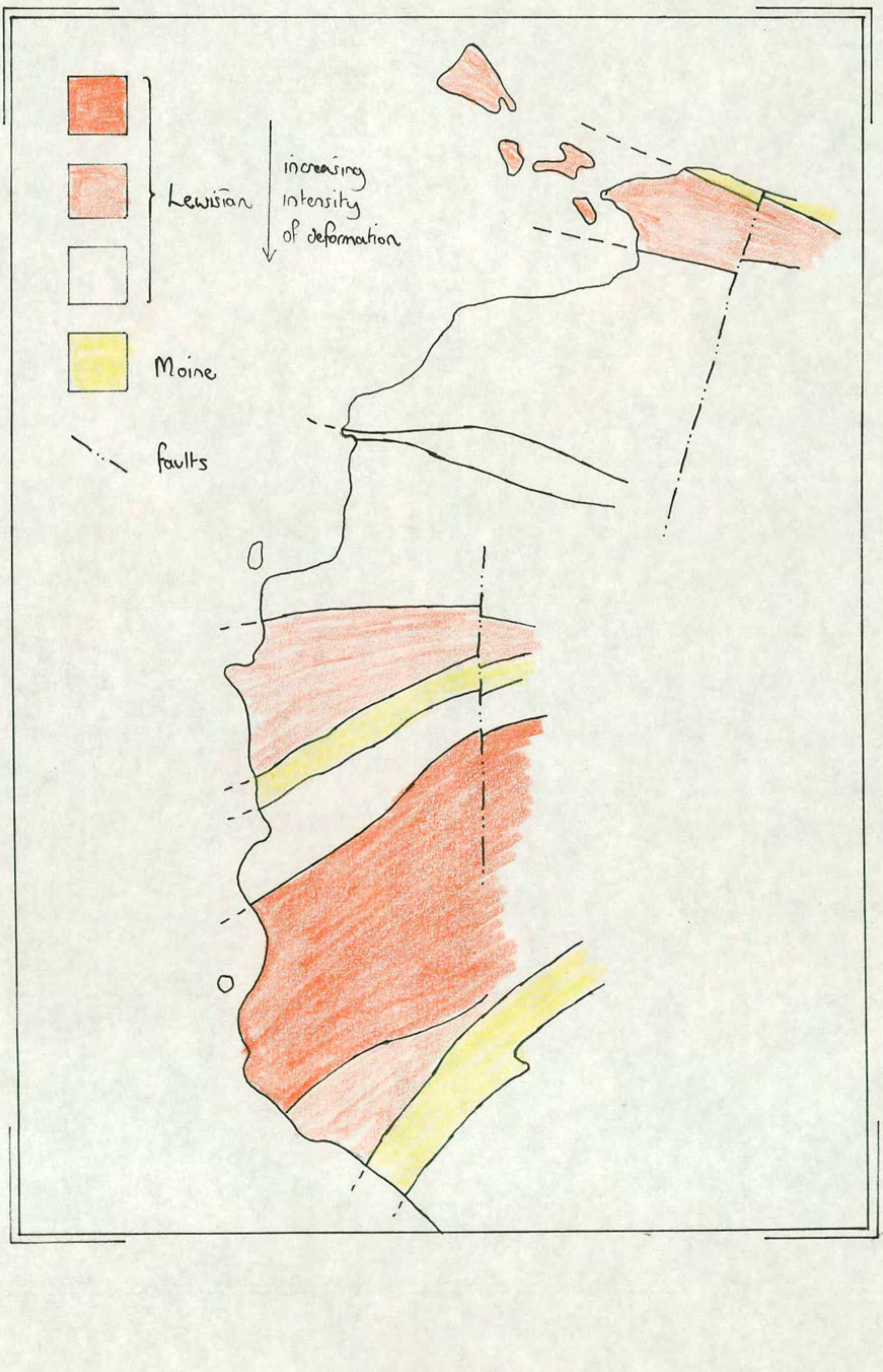
7.2 Field descriptions

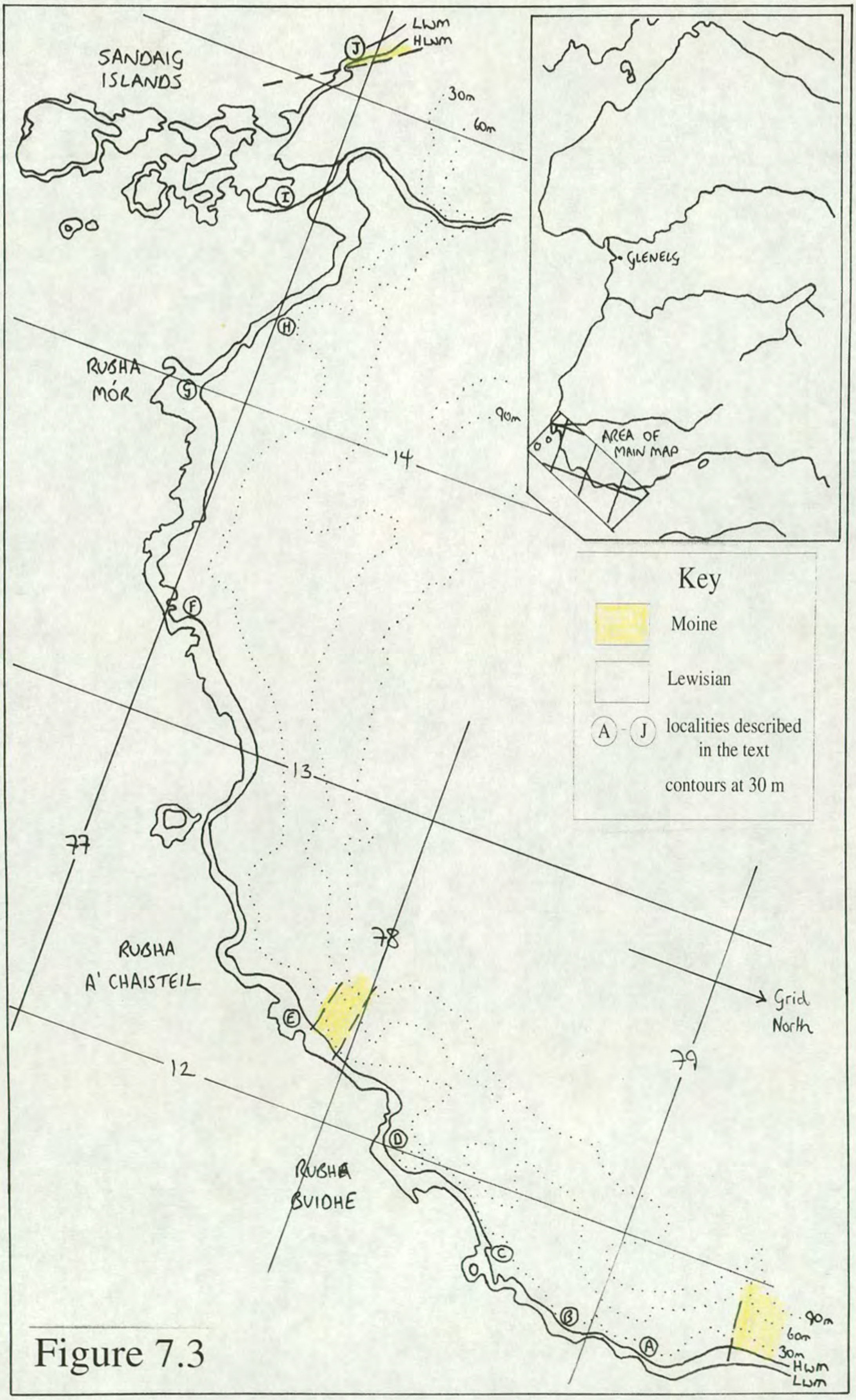
7.2.1 Eclogites and other garnet - bearing rocks

The most striking rocks in the Western Lewisian are the eclogites. These are exposed close to the Sandaig Islands at the Rubha Mor, GR 767140, locality G, figure 7.3, at the mouth of Loch Hourn. Sanders (1972) describes loose blocks of eclogite occurring along a boulder beach to the north of the Rubha Mor, but does not describe finding *in situ.* eclogite. It occurs in at least seven pods of varying size that occur over an area about 300 square metres. Most of the pods are small, only up to a metre across, but two pods at GR 769142 are both about 3 metres across and 10 metres long (plate 7.1.A). The cores of these bigger pods consist of a weakly foliated garnet - pyroxene - quartz rock, containing roughly equal proportions of garnet and pyroxene crystals up to 3 mm across, with smaller, less common quartz. In one pod the eclogite is patchy with garnet rich and pyroxene rich areas. The eclogite is cut by dark hornblende filled cracks up to 1 cm across, some of which have a pale yellow core of actinolite and epidote (plate 7.1.B). Narrow epidote - actinolite filled cracks up to 0.2 mm across occasionally occur without an obvious zone of alteration alongside. Occasionally these cracks are cut by later microfaults with have offsets of up to 2 mm. Towards the rims of the Western Lewisian pods there is a progressive change from eclogite to garnet amphibolite and then to epidote - amphibolite at the pod rim. The smaller pods show similar changes.

Figure 7.2 (following page) : Sketch map of the extent of deformation in Lewisian rocks on the N coast of Loch Hourn from Camas na Ceann to Sandaig (after Ramsay, 1957).

Figure 7.3 (second page) : Sketch map of the N coast of Loch Hourn from Camas na Ceann to Sandaig with localities mentioned in the text.


Lewisian
increasing intensity of deformation
Moine
faults



SANDAIG ISLANDS
LWM
HWM
30m
60m
GLENELG
AREA OF MAIN MAP
RUBHA MÓR
90m
14
Key
Moine
Lewisian
A - J localities described in the text
contours at 30 m
13
77
78
RUBHA A' CHAISTEIL
Grid North
12
79
RUBHA BUIDHE
90m
60m
30m
HWM
LWM

Figure 7.3

North of Loch Alsh and Loch Duich, Barber and May (1975) described patches of garnet - pyroxene bearing granulite facies rocks within retrogressed amphibolite facies schists. These are fairly coarse grained and consist of dark red garnet up to 1 cm across in a slightly finer matrix of foliated pyroxene, green amphibole, quartz and feldspar.

Other garnet bearing rocks in the Western Lewisian are rare. Along the coast of Loch Hourn they occur in only two other localities. One of these localities, locality I, figure 7.3, is on the east side of Eilean Carach, GR 768146, one of the Sandaig Islands, close to the eclogite outcrop. It is a fine grained quartz - feldspar rich rock with randomly orientated needles of black amphibole up to 3 cm long, and with small, pink, equant garnets a few mm across. The other locality, locality E, lies some two miles east at GR 777123. Here, dark green, foliated, amphibole rich rocks contain small, pink, euhedral garnets up to 2 mm across.

7.2.2 Other Lewisian rock types.

The bulk of the Western Lewisian consists of layered, foliated quartz - feldspar - hornblende gneiss. These layers are of variable thickness, generally on a fine mm scale (plate 7.1.C) but in places bands up to 50 cm or more thick, either of pale quartz - feldspar rich rock with little hornblende or biotite, or of dark amphibole rich rock with or without biotite but with little quartzo - feldspathic material. The garnet - bearing amphibolite of GR 777123, locality E, is similar to this. Around GR 783119, locality D, figure 7.3, the dominant rock type is a quartz - feldspar rich rock with only occasional thin layers of amphibole and biotite.

Throughout this foliated material there occur bands and pods of different types of rock, including eclogite, which has already been described, massive or foliated amphibolites, biotite rich rocks, and amphibolitic rocks devoid of quartz and feldspar. At a few localities where later deformation has been less intense, these latter rocks show cross cutting relationships to the surrounding plagioclase - amphibolite.

Pods of fine grained, massive or foliated, quartz - feldspar bearing amphibolite occur often in association with the eclogite pods. Where foliated, the weak foliation is outlined by streaks of quartzo - feldspathic material. In places bands of massive basic rock occur as boudins within schistose quartzo - feldspathic rock, such as at GR 784147, inland from Sandaig bay (plate 7.4.A).

Just west of Port an Tairbh, (locality B, figure 7.3), GR 791117, pods of migmatitic hornblende - quartz - feldspar gneiss occur. These appear to be the least deformed rocks on the coast section. They consist of large areas of dark amphibole rich rock that are cut by anastamosing layers of quartzo - feldspathic material (plate 7.2.A). These pods of migmatite occur up to 10 m across and pass in all directions into the fine grained foliated amphibole - quartz - feldspar rock that makes up most of the Western Lewisian. Occasional pods of migmatite occur elsewhere within foliated rocks. At Dornie, on the north side of Loch Duich, a new road cutting has exposed a small amount of fresh outcrop, most of which is quartzo - feldspathic rich migmatite, containing small elongate clumps of black amphibole and biotite, up to 3 cm across and 10 cm's long. These clumps outline a weak foliation (plate 7.4.B).

Other common rocks forming pods and sheets are shiny, dark black, hornblende - rich rocks, virtually devoid of any other mineral, but occasionally with biotite. These normally occur as small pods up to 1 metre long within foliated quartz - plagioclase - hornblende rock (plate 7.2.B). They consist of coarse hornblende needles up to 5 mm long that are generally randomly oriented in a massive rock, but which are sometimes oriented to define a weak schistosity. Commonly this rock type is extremely soft and friable. Where this material forms sheets in the foliated quartz - feldspar - amphibole rock, the sheets often appear to be slightly oblique to the foliation. At GR 789116, locality A, figure 7.3, a large mass of this material cuts across strongly foliated amphibole - quartz - feldspar rock, clearly terminating quartz - feldspar bands within the host rock (plates 7.2.C & 7.4.C). At this locality the hornblendite cuts across a foliated amphibole - quartz - plagioclase rock, but also carries a weak fabric parallel to that in the host rock.

Another common type of nodule consists of shiny coarse green amphibole with or without biotite and rare quartz. This rock generally occurs as both pods and sheets in the foliated rock. In areas of stronger deformation the sheets are folded with the surrounding rocks, and have a lineation and often a weak axial planar cleavage. The rims of these sheets often contain clumps of dark biotite. Where the rock forms pods it tends to consist almost entirely of pale green actinolite as randomly orientated crystals up to 1 cm long.

At GR 777123, (locality E, figure 7.3) near to the Rubha a' Chasteil, there are good examples of both cross cutting relationships and of a composite pod. A band of shiny dark amphibolite 15 cm thick and carrying a weak foliation cuts across a number of the quartz - feldspar bands in the accompanying schistose amphibole - garnet - quartz -

feldspar rock (plate 7.3.A). Both of these rock types are cracked, some of the cracks being filled by K - feldspar. Nearby is a composite pod consisting of massive shiny black amphibole, of foliated biotite - plagioclase with some amphibole, and of a soft pale green amphibolite of coarse randomly oriented actinolite needles. All of these occur as sub parallel, interleaved layers within the pod (plate 7.3.B).

Much of the deformation that occurred along the coast section has produced strongly foliated rocks, but folds do occur. The earliest deformation to affect the whole area, including Moine rocks, produced a strong fabric along with rare isoclinal folds parallel to the foliation (plates 7.3.C & 7.4.D). This fabric is later deformed either by small scale crenulations of amplitude <1 cm, with a weak cleavage developed on the earlier fabric, or by more large scale folds. The former are well seen along the east side of Sandaig bay, locality H, figure 7.3, the latter around Rubha Bhuide, locality D, figure 7.3. Coarse randomly orientated needles of amphibole and plates of biotite both up to 1 cm long commonly grow over the schistosity and the crenulations.

At Rubha Bhuide, two generations of folds can be seen in rocks consisting of thick sheets of amphibole - quartz - feldspar separated by thin bands of quartzo - feldspathic material. The former are up to 1 m across, and consist of dark amphibole with or without biotite and subordinate quartz and plagioclase. The latter are thin sheets of fine grained quartz - feldspar - biotite - epidote rock, generally only a few cm across, although some thicker bands do occur. Both these rocks have a strong foliation that has been folded twice. The first set of folds are tight and have a strong lineation parallel to the hinges and a weak axial planar cleavage. These folds commonly plunge towards the NE (plate 7.5.A). The second set refold these folds and the lineation, and plunge towards the SE. Immediately to the west of this locality, at GR 781122, the sheets of fine grained quartz - feldspar - amphibole rock are boudinaged. In a road cutting at GR 792167, inland NE of Sandaig, these folding relationships are well seen (plate 7.5.B), along with boudinage of massive fine grained amphibolite which cuts across the fabric of the foliated amphibole - quartz - feldspar rock (plate 7.5.C).

7.2.3 Moine rocks

The Moine rocks crop out in a thin strip approximately halfway along the coast section on Loch Hourn, (marked on figure 7.3.) and NW of the Sandaig islands, at GR. 769152, (locality J, figure 7.3.) In the former case the rock is a quartzo - feldspathic rock with some mica that has a strong schistosity, making it hard to distinguish from the surrounding Lewisian rocks. In the latter case, the contact with the Lewisian rocks occurs in a vegetation - filled gully and is not exposed. Here the Moine is a fine grained garnet - bearing pelite. The garnets are small, equant, pale red crystals a few mm across in a matrix of schistose quartz - mica - feldspar, with some randomly oriented needles of (apparently) amphibole a few mm long. The schistosity is defined by the mica flakes. This schistosity is crenulated, and carries a lineation.

7.3 Evidence for nature and age of possible dykes

In section 7.2.2 the cross - cutting relationships between massive basic and ultrabasic rocks with surrounding schists within the Western Lewisian were described These relationships within the Western Lewisian are beyond doubt, and have been further described by Ramsay (1958) and Sanders (1972). Sanders suggested that because a basic rock cutting across schists had a similar chemistry to the eclogites they were of similar origin. He did not appear to consider differences in texture or mineralogy, in particular that cross - cutting rocks within the Western Lewisian are rutile free, a phase that is virtually always present as cores to sphene in sphene - bearing rocks derived from eclogite. The question as to whether these dykes were or were not metamorphosed to eclogite facies has not been previously considered.

As with the Eastern Lewisian, the problem is that there is negative evidence that suggests the rocks have not suffered eclogite facies metamorphism, but there is no real positive evidence. The evidence is similar to that discussed in section 6.7.4 for the Eastern Lewisian. There is no evidence of former garnet, clinopyroxene or rutile (chapter eight) and the cross - cutting rocks have different chemistries to other Western Lewisian rocks (chapter nine).

7.4 Interpretation and discussion

The history of the Western Lewisian eclogites is hard to describe in full from field observations because of their limited occurrence as pods. Sanders (1972) assumes that all the pods within the amphibolite schist regardless of mineralogy are of similar age and that the eclogites are thus similar to hornblendite and actinolitite pods. The similarity seen in the field between the Western Lewisian eclogites and those occurring within the Eastern Lewisian, particularly those described in chapter three along the shore of Loch Duich at Fern Villa, means it is possible that these eclogites have a similar history to those in the Eastern Lewisian. Possible correlation between the "amphibolitites" and the eclogites will be discussed in chapter nine.

Other than the eclogites, the oldest rocks seen in the Western Lewisian are the migmatites seen in the relatively undeformed eastern end of the section, that pass into foliated quartz - feldspar - amphibole - biotite rocks. It is likely that this material represents some initial basic rock type that has been injected by quartzo - feldspathic material at an early period in its history. Barber and May (1975) interpreted similar rocks found north of Loch Alsh as being the retrogressed equivalent of rare granulite facies rocks and tentatively linked the granulites in the north with the eclogites in the south. Any relation between the migmatites, the eclogites and the eclogites cannot be determined in the field, therefore these relationships will be discussed later after a description of their petrology and chemistry in the next two chapters.

The migmatite was deformed, and is seen to pass out in all directions into foliated amphibolite. At locality A, figure 7.3, GR 789116, the relative history of most of the rocks in the Western Lewisian can be demonstrated. Here the intrusion of 'new' basic material is seen to occur after this early deformation because it cuts a foliation in the surrounding rocks. Both host and newly intruded rock types were then deformed together producing a diffuse, contorted boundary between the two rocks, forming a strong foliation in the host rock and a weak foliation in the intruded material.

The deformation affecting both deformed migmatite and intruded basic material is the earliest deformation to affect all the rocks in the area, including the Moine rocks. It is probably responsible for forming pods or boudinaged sheets of basic material within strongly schistose rocks. Later deformation has resulted either in the further shearing of these schistose rocks, producing lineation or crenulation cleavage, or more rarely produces tight folds with a lineation parallel to the hinge, and with a weak axial planar cleavage. In many rocks there has been the growth of random amphibole, biotite, and rarely, garnet over the schistose fabric. All of this material is then folded by a further set of folds.

This sequence of deformation correlates with that of Ramsay (1957, 1963) and, broadly speaking, with that outlined for the Eastern Lewisian in chapter three. An early D_0 event effected the Lewisian prior to the intrusion of basic dykes, but did not effect the Moine. Regional D_1 is the first deformation event to effect both the Moine and the Lewisian. D_2 is of variable style, often producing a strong fabric, but in places forming minor folds. D_3 is the final stage of folding, which refolds D_2 folds, and folds the lineation. The details of possible correlation between the Eastern and Western Lewisian will be discussed in the conclusions.

Barber and May (1975) interpreted Western Lewisian rocks from north of Loch Alsh as being migmatites that had suffered two periods of granulite facies metamorphism, the first with stable pyroxene, the second with stable hornblende. These rocks were then intruded by a suite of basic and ultrabasic dykes that were not metamorphosed to granulite facies. The Moine rocks were then deposited on the eroded surface of the Lewisian. All the above rocks were then deformed on a number of occasions and metamorphosed to amphibolite facies. No evidence was presented for pre - Moine deformation within the Lewisian, but the sequence of events as a whole is similar to that affecting the Scourian rocks of the foreland and Barber and May (*op cit.*) made correlations between the two.

Plate 7.1.

A) Eclogite pod at Sandaig, GR 769141, looking N. (Yellow is predominantly lichen), with foliated amphibolite (right).

B) Detail of pod rim, plate 7.1.A. Edge of pod (top) is 15 cm of dark amphibolite. Rest of pod is predominantly pale eclogite, but with wide zones of dark amphibolite. The eclogite is cut by dark amphibole filled cracks and by pale epidote - actinolite filled cracks with alteration alongside them (centre).

C) Western Lewisian amphibolite schist with thin hornblende rich and plagioclase rich bands, and clots of feldspar. Some isoclinal folding parallel to the schistosity. North shore of Loch Hourn, GR 850079, scale oriented N-S

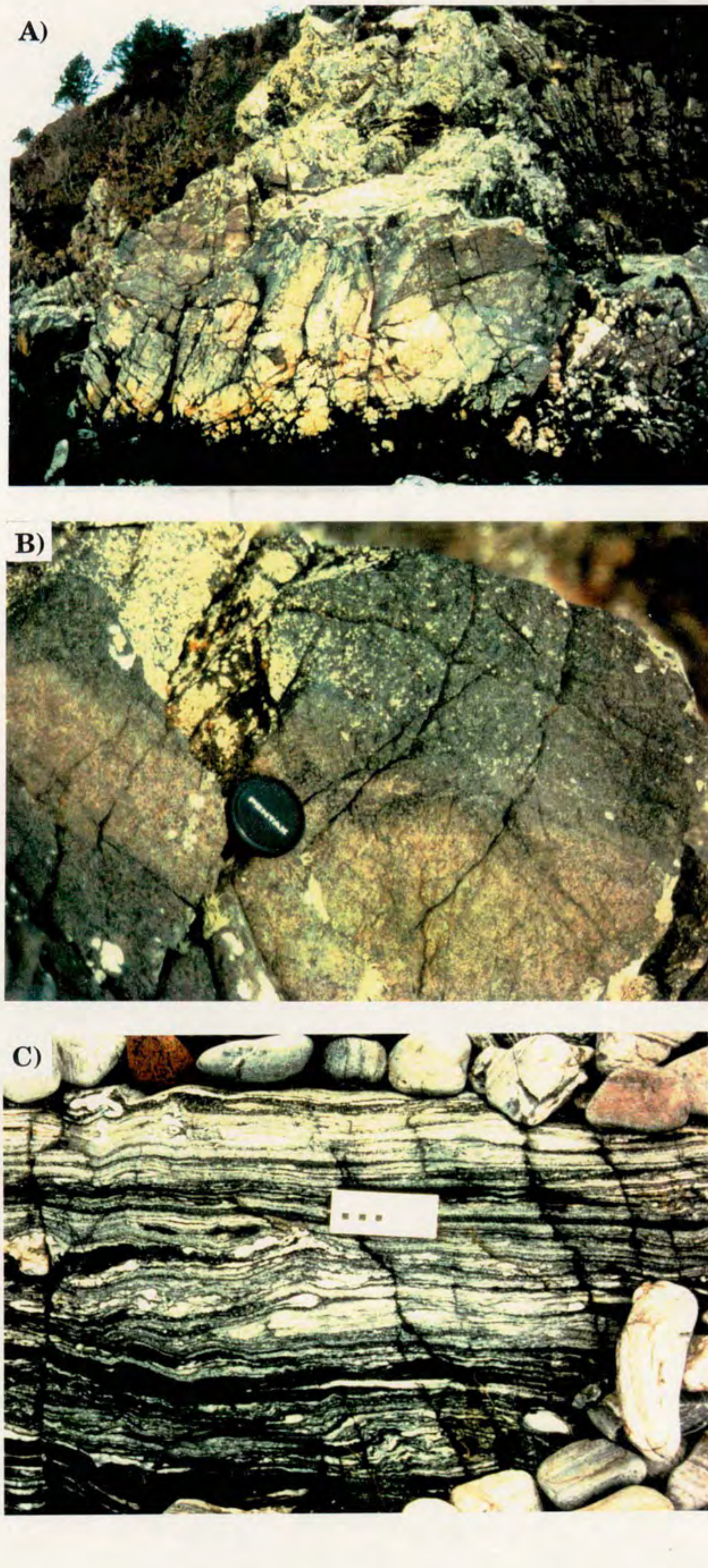

A)
B)
PENTAX
C)

Plate 7.2

A) Pod of dark amphibole - rich rock invaded by quartzo - feldspathic rock, surrounded by schistose amphibolite. North shore of Loch Hourn, GR 791117, looking N.

B) Schistose amphibolite with pods of dark "amphibolitite". North shore of Loch Hourn, GR 783119, looking N.

C) Schistose amphibolite (top) with layering cut by dark "amphibolitite" layer, north shore of Loch Hourn, GR 789116, looking NE.

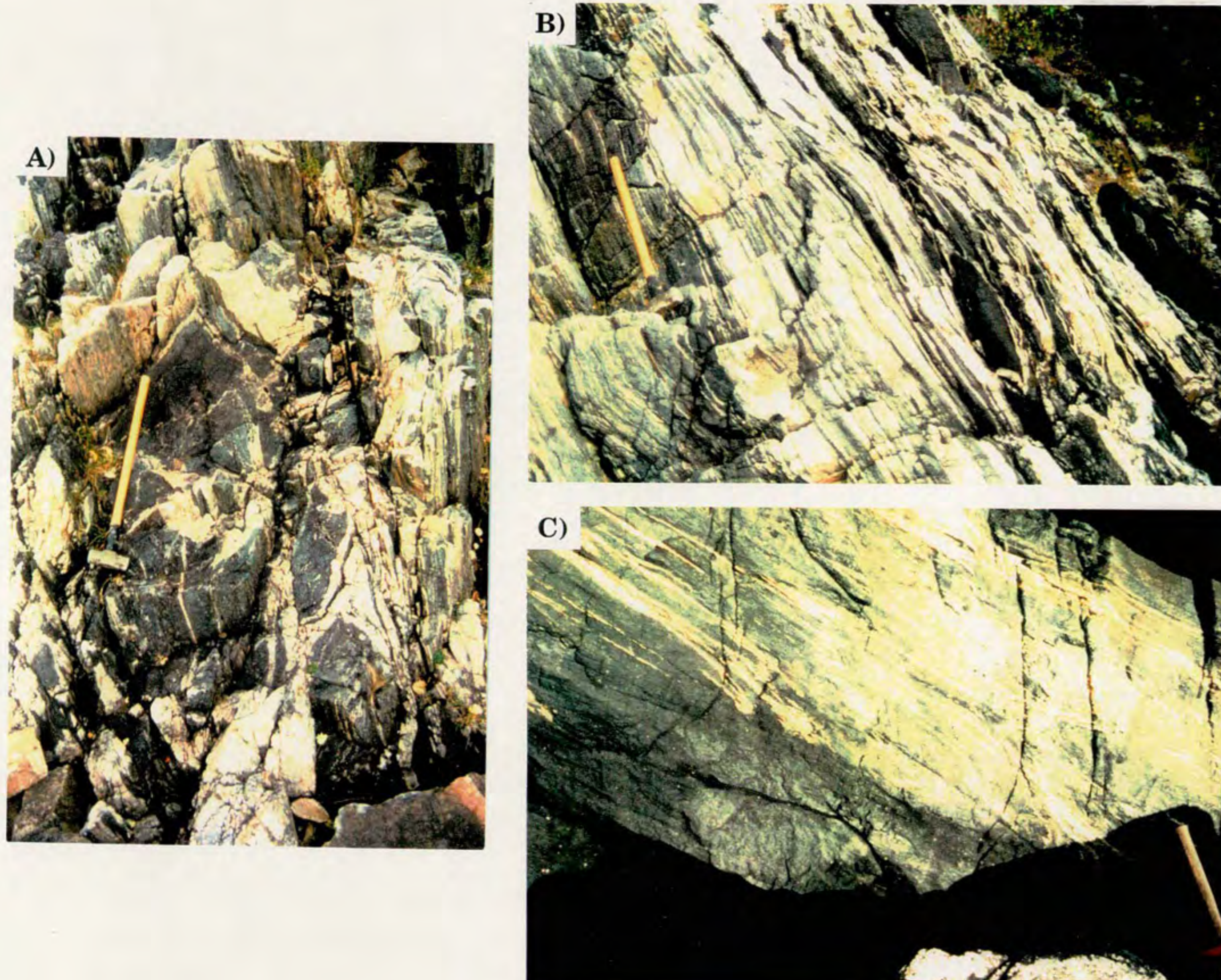

A)
B)
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Plate 7.3.

A) Schistose amphibolite with cross - cutting band of dark "amphibolitite". Cross cutting relations are nearly obliterated by later deformation. North shore of Loch Hourn, GR 778122, looking E.

B) Composite pod within schistose amphibolite. Biotite rich rock (yellowish, centre) and "amphibolitite". North shore of Loch Hourn, GR 778122, looking E.

C) Intensely deformed amphibolite with strong fabric and isoclinal foliation parallel folds. North shore of Loch Hourn, GR 852084, looking E.

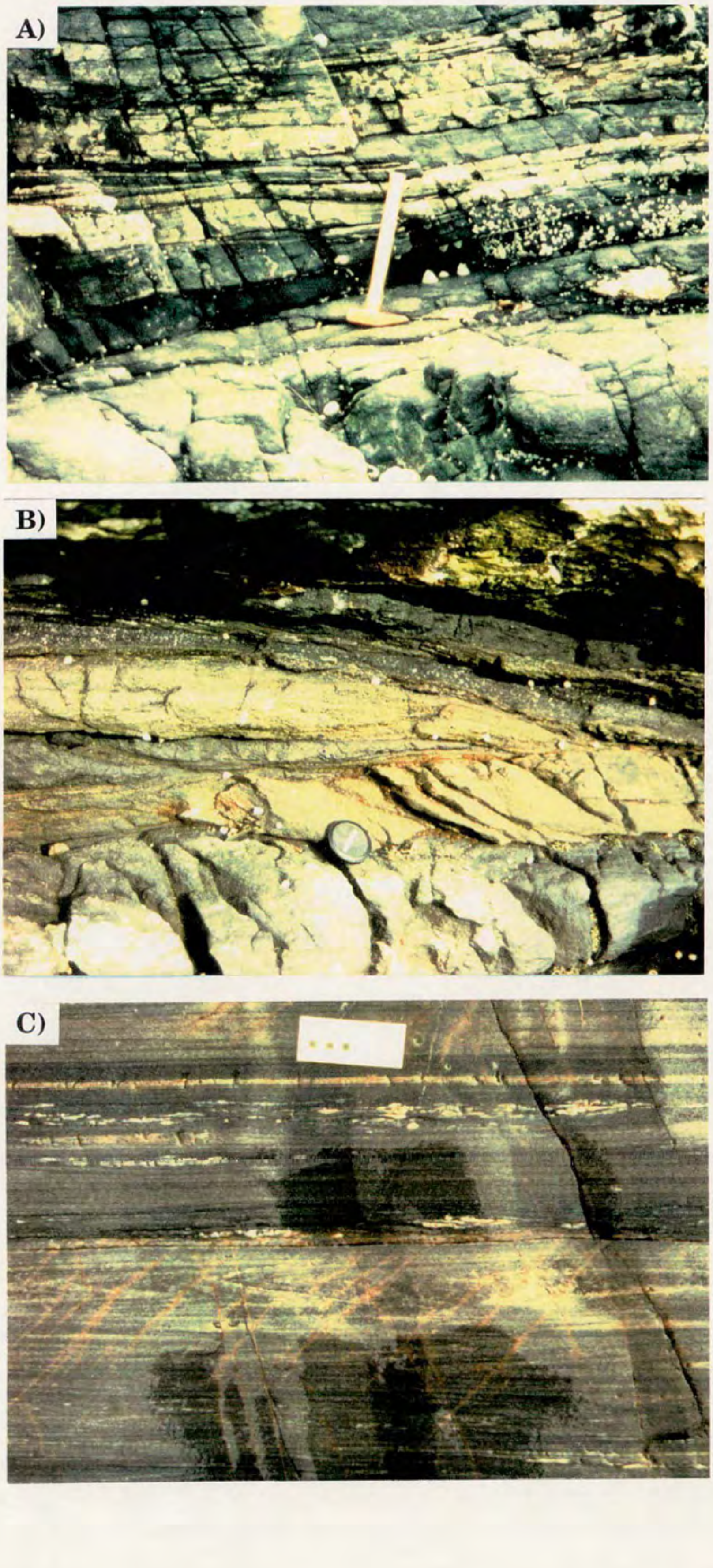

A)
B)
C)

Plate 7.4.

A) Massive amphibolite pod within schistose amphibolite, Sandaig, GR 769141. Hammer is oriented approx. N-S.

B) Feldspar rich migmatite from the Western Lewisian north of Loch Duich, GR 883263, looking E.

C) Schistose amphibolite with layering cut by dark "amphibolitite". Contact is disturbed by later deformation (see plate 7.2.C). North shore of Loch Hourn, GR 789116, looking N.

D) Minor foliation - parallel fold within schistose amphibolite wrapping a massive amphibolite pod, Sandaig, GR 769141. Hammer is oriented approx. N-S.

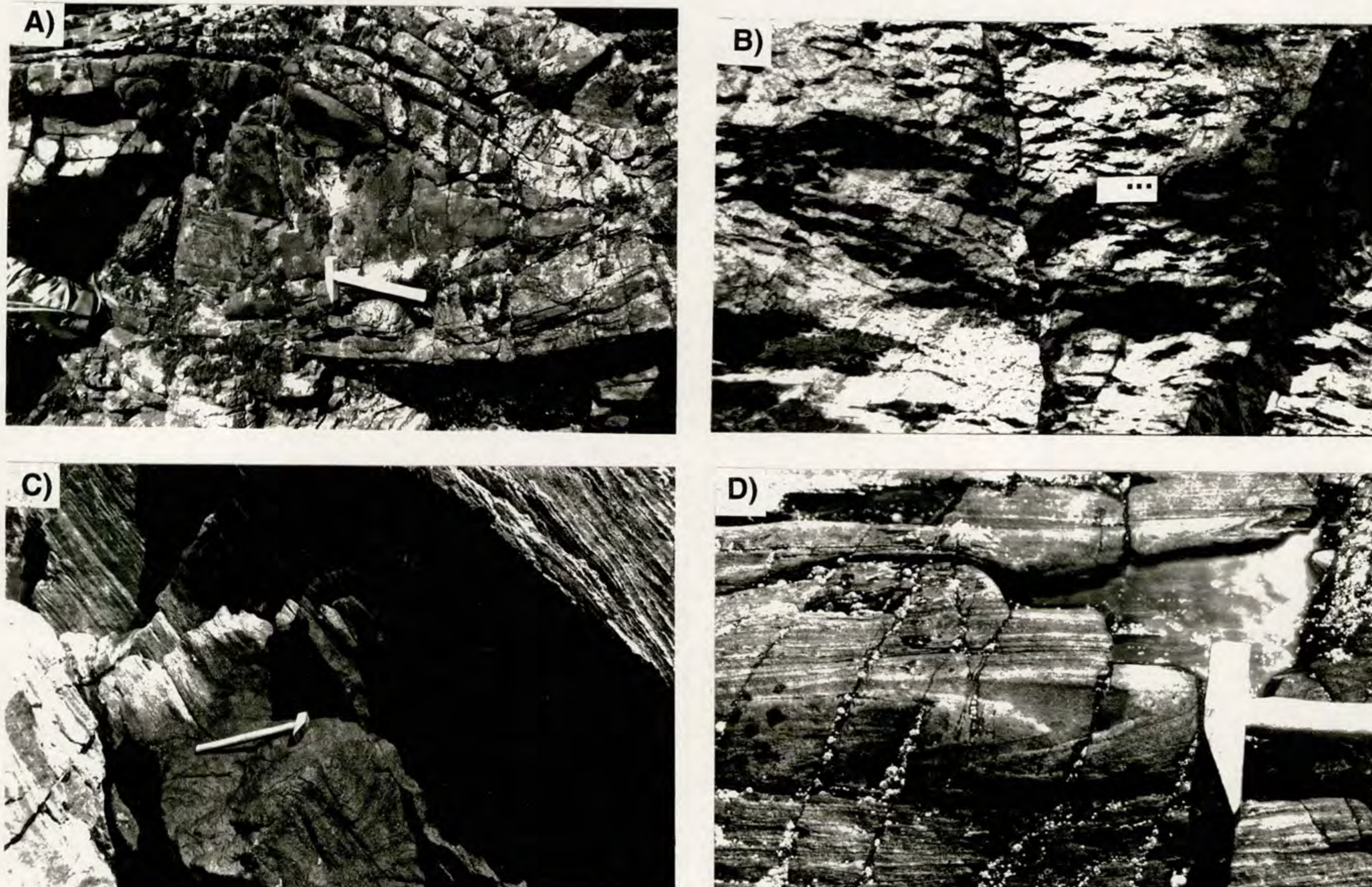
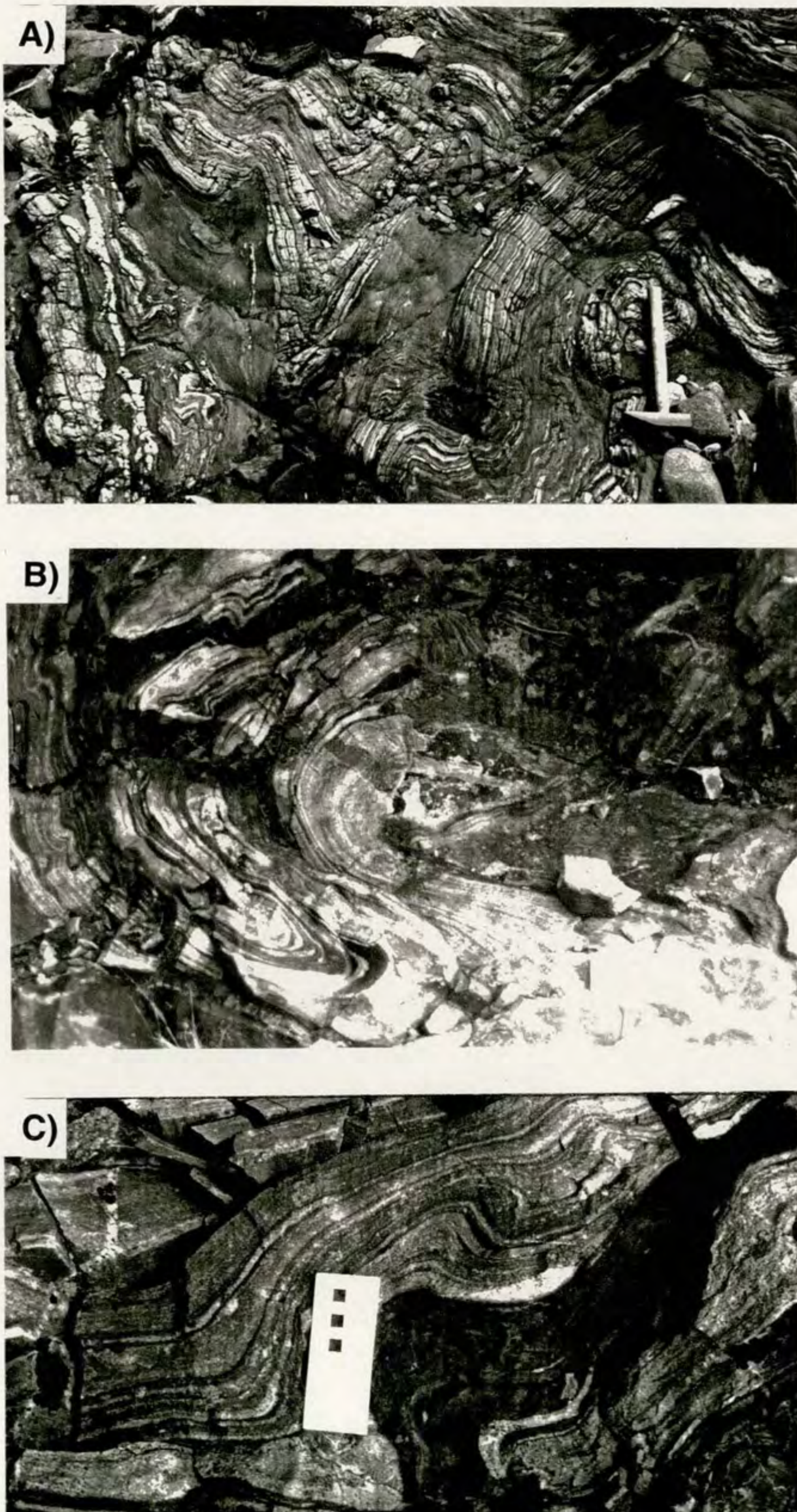

A)
B)
C)
D)

Plate 7.5.

A) Folded schistose amphibolite, north shore of Loch Hourn, GR 782121. Hammer is oriented approx. E-W.

B) Refolded schistose amphibolite, tight D_2 folds deformed by more open D_3 folds. GR 784147, looking E.

C) Dark band of massive "amphibolitite" stretched and boudinaged within schistose amphibolite. GR 784147, looking E.


A)
B)
C)

Chapter Eight

Petrography of the Western Lewisian rocks

CHAPTER 8

Petrography of Western Lewisian rocks

8.1 Introduction

In chapter seven the field relationships of the Western Lewisian rocks were described. The bulk of the rocks making up the area are schistose amphibolites composed of variable proportions of amphibole, feldspar, quartz and biotite. Within these rocks there occur pods of basic rocks including (at one locality) eclogite, rare garnet amphibolites, massive or foliated amphibolite with plagioclase (termed plagioclase - amphibolite), and amphibolite of pure amphibole (termed "amphibolitite"). Minor biotite - rich rocks also occur. The relationships between the pod - forming rocks, particularly the eclogites, and the host rocks were not clear. The structure of the area was summarised in chapter seven, after May *et al.* (1993) and discussion in chapter two. There was an early (D_0) deformation prior to the possible intrusion of the "amphibolitites" as basic dykes. Later deformation affected both Moine and Lewisian rocks with three main events (D_1 - D_3) and a minor D_4 event.

8.2 Eclogite petrology

Eclogites only occur within the Western Lewisian at Sandaig, GR 769141, where a number of pods of eclogitic material occur within foliated amphibolites. The largest pods consist of fairly fresh eclogite, whilst other smaller pods represent partly retrogressed eclogite. The freshest eclogites are described first, followed by descriptions of the mineralogical changes that have occurred with retrogression.

8.2.1 Fresh eclogite

SN.'s 414 - 420 represent a transect in from the rim of a large 10 m wide pod sampled every 5 cm, including samples from a wide zone of alteration to amphibolite (SN. 416).

SN. 252 consists of round pale pink garnets up to 2 mm across occurring with anhedral pale green pyroxene and patches of irregular sutured quartz, both up to 1 mm across (plate 8.1.A). Garnet is often full of quartz inclusions and more rarely has pyroxene inclusions. Often garnet occurs as smaller polygonal crystals up to 1 mm across. Irregular patches of plagioclase - biotite symplectite occur throughout. They are of variable size, up to 3 mm across, often occurring with fragments of garnet and pyroxene. The biotite is sometimes altered to chlorite. The plagioclase is generally dusty. Throughout the rock pyroxene, plagioclase and quartz are all highly strained. SN. 418 is more coarse grained, with garnet up to 3 mm across separated into subhedral grains by quartz and dark green amphibole. Pyroxene occurs as aggregates up to 1.5 mm across consisting of fine grained crystals, often with quartz and amphibole. Patches of clear polygonal quartz up to 2 mm across are more common than in SN. 252, whilst plagioclase - biotite symplectites are less common (plate 8.1.B). These two samples are the freshest eclogite seen within the western Lewisian. In both samples pyroxene never - the - less appears to coexist with plagioclase.

In other, smaller pods cracks filled by amphibole and plagioclase are more common and make up a large proportion of the rock. Garnet and pyroxene remain only as patches between the cracks, where clinopyroxene is often altered to a fine grained symplectite (plate 8.1.C).

8.2.2 Retrogression of the eclogite.

Retrogression of the western Lewisian eclogite occurs in a similar manner to that described for the eastern Lewisian, whereby the rock is affected either by patchy alteration to form hydrous minerals within the bulk of the rock, or by alteration alongside cracks which are filled by various mineralogies. The only major difference is that symplectites after clinopyroxene are rare, with pyroxene mostly altered directly to amphibole and quartz. The larger pods are retrogressed at their rims and cracked in their cores. Smaller pods are variously retrogressed throughout.

The earliest set of cracks leads to the alteration of pyroxene to form amphibole with either quartz or plagioclase. This occurs in zones of alteration, usually no more than 3 mm across, in which garnet remains stable, but pyroxene is completely replaced by coarse grained hornblende with many fine inclusions of quartz. In SN. 420 at the rims to these zones of alteration rare moats of plagioclase occur between garnet, quartz and remnant pyroxene (plate 8.7.A).

Later cracks are filled by epidote and actinolite. Alteration has occurred either side of these cracks, usually up to 5 mm away from them. The alteration produces amphibole, epidote and plagioclase. Usually these cracks are narrow, up to 0.1 mm across, but they occasionally occur up to 1 mm across, as in SN. 356 with coarse epidote and actinolite (plate 8.1.D). SN. 416 represents an unusually thick zone of alteration either side of an epidote - filled cracks, with alteration occurring in a zone 3 cm wide.

A third set of cracks often occurs, with a fill of K - feldspar, stilpnomelane and quartz, with occasional chlorite and calcite. Sometimes there is a small offset across the cracks, seen where they cut earlier cracks.

The more extensive alteration that has occurred at the rims of pods is seen in SN.'s 414 and 415. In SN. 415, the eclogite is almost completely altered to coarse grained amphibolite consisting of clear plagioclase and pale green inclusion free amphibole, both of which are up to 1.5 mm across. Some sieved amphibole occurs, although with vermicular quartz rather than with more usual rounded blebs. Knots of chlorite after garnet occur throughout, occasionally with relict garnet cores, sometimes with cores of epidote - amphibole symplectite. Biotite - plagioclase symplectite is common, although some of the biotite is altered to pale green chlorite (plate 8.2.A). The most retrogression has occurred in SN. 414. This is mainly an amphibole - chlorite - quartz - feldspar rock. It consists of roughly 50 % dark green amphibole up to 1.5 mm across, sometimes with small quartz inclusions, and epidote, either with plagioclase and/or amphibole, or as fine grained subhedral crystals up to 0.5 mm across and full of quartz crystals. The rest of the rock consists of feldspar, quartz and chlorite with some biotite and epidote. Quartz is segregated and occurs in patches up to 2 mm across of smaller strained, irregular grains. Plagioclase is dusty and strained, and occurs with chlorite and rare biotite symplectites (plate 8.2.B).

Alteration in smaller pods is similar to that described for the largest pod, above, but without any remaining fresh eclogite. Omphacitic pyroxene is not found, rather fine grained symplectites of diopside and plagioclase occur. Garnets tend to be small, subhedral and inclusion free. The smaller pods are mostly composed of material similar to SN.'s 414 and 415. A few pods are entirely amphibolitised pod that has a rim of garnet - amphibolite. SN. 401 from the core of the pod is similar to SN. 414. SN. 402 from the rim of the pod consists of 60 % polygonal quartz and feldspar up to 0.25 mm across. Much of the feldspar is dusty. The rest of the rock consists of amphibole, biotite, sphene, epidote and garnet. The rock is layered into comparatively quartz - feldspar rich and poor layers. Amphibole occurs as large dark green crystals up to 1 mm across, often with inclusions of biotite, plagioclase, epidote and quartz. Biotite occurs in a similar manner but is often altered to chlorite. Epidote occurs throughout as subhedral grains of variable size, up to 0.5 mm across. Smaller crystals are full of minute inclusions. Larger crystals have inclusion - free cores, but rims full of inclusions (plate 8.2.C). Sphene is rare, usually occurring as ragged crystals up to 0.5 mm across containing rare ilmenite cores.

8.2.3 Summary

The eclogites show textures similar to those described in the Eastern Lewisian along the SW shore of Loch Duich near to Fern Villa, with occasional coarse garnet and pyroxene partly altered to a garnet - clinopyroxene - plagioclase - biotite - (hornblende) assemblage. Alteration for the most part has occurred with the formation of two sets of cracks. The first contain amphibole and feldspar from the breakdown of pyroxene, the second contain epidote and actinolite from the breakdown of garnet and the alteration of hornblende. Progressive alteration seems to have occurred at the edges of the pods to form similar assemblages at the rims to eclogite pods as those seen within cracks cutting the cores of the pods, with pyroxene altered to plagioclase and amphibole and some alteration of garnet to chlorite, then with garnet altered to epidote and amphibole.

8.3 Amphibolite petrology

Amphibolites form the bulk of the rocks of the Western Lewisian. They can be divided into five groups in the field: garnet - amphibolites, plagioclase - amphibolites, biotite - amphibolites, quartz - feldspar - mica rocks, and "amphibolitic" rocks. The petrology of each of these rock types is considered separately.

Garnet bearing amphibolites are rare, and have only been found at three localities. The first of these is associated with the retrogression of the eclogite and has already been described in section 8.2.2 above. The second occurs in metabasic rocks at GR 776124, and the third in more acidic rocks at GR 768146 on Eilean Carach, close to the eclogite locality. These are described with the relevant related garnet - free amphibolites

8.3.1 Plagioclase - amphibolite

The bulk of the western Lewisian consists of banded plagioclase - hornblende amphibolites with quartz and varying proportions of biotite and epidote. Normally this banding is on a fine, thin section, scale, although quartz - feldspar rich bands up to 1 metre across are common, and at one locality form a band 25 metres across.

The metabasic garnet amphibolite of GR 776124 is a garnet - hornblende - biotite - quartz - feldspar - sphene rock. At this locality there are at least two outcrops of garnet - amphibolite (RC1, RC2 and 446, 447) In SN. RC2 hornblende and biotite both occur as elongate crystals greater than 1 mm long and up to 0.2 mm across that define a weak fabric along with streaks of fine grained sphene. Rare larger hornblendes are sieved, full of quartz inclusions. The amount of quartz and feldspar is variable, with quartz - feldspar richer and poorer patches, although the distribution of these is not related to the fabric. Quartz, feldspar and large hornblendes are all either strained, or else occur as larger crystals divided into subgrains. Garnet occurs throughout as large anhedral crystals up to 3 mm across full of tiny inclusions of quartz, sphene, opaques and epidote (plate 8.2.D). These inclusions occur in parallel bands, oblique to the weak foliation now outlined by hornblende and biotite which now wraps around the garnets. Smaller anhedral, inclusion free crystals of garnet up to 0.3 mm across also occur. SN. 447 is similar, but with epidote and only rare garnet. The rock is rather more hornblende rich, has a weaker fabric, and contains many small epidote crystals with the quartz and feldspar. It is cut by feldspar - stilpnomelane veins. SN. RC3 is a garnet rich, biotite poor rock, with much of the biotite partly altered to chlorite. Garnet occurs with many quartz and sphene inclusions, but is often partly altered to feldspar and chlorite. SN. 446 is similar to SN. RC3, but contains much epidote, as tiny euhedral inclusions to all phases. This rock is also cut by feldspar - stilpnomelane veins.

A number of the plagioclase - amphibolites throughout the coast section are similar to both the retrogressed eclogite and the above garnet - amphibolite. They are coarse grained with either no foliation or only a weak fabric, and consist of patchy quartz - feldspar rich parts and amphibole - biotite rich parts, with fine grained sphene throughout (plate 8.3.B). SN. 372 (GR. 778124, one of the migmatite pods, chapter seven) is such a rock, and consists of rounded amphibole up to 3 mm across with many inclusions of quartz, sphene and epidote, and symplectites of amphibole - epidote - feldspar after garnet. Occasionally large biotite crystals up to 2 mm across also occur. Quartz and feldspar are both polygonal, usually unstrained, with many tiny epidote crystals occurring as inclusions to feldspar, and between grains. Larger epidotes up to 0.25 mm across are zoned. The whole rock is cut by plagioclase - actinolite filled cracks. SN.'s 358 and 359 both occur as pods immediately adjacent to one of the large eclogite pods at Sandaig and are similar to SN. 372. SN. 358 contains calcite within the body of the rock. It is cut by feldspar bearing veins. SN. 359 has large round crystals of sphene, often with rutile cores, and is cut by feldspar - calcite filled cracks. SN. 366 contains more biotite than the above rocks, often occurring as symplectites with epidote, probably after garnet. SN. 208 is a fine grained, foliated rock, but never the less, it bears a resemblance to the eclogites. It consists of quartz - feldspar rich layers with some epidote and chlorite, and layers rich in amphibole - epidote - biotite - sphene. The rock is cut by epidote filled cracks.

Other rocks do not bear such a resemblance to retrogressed eclogite, but still consist of amphibole - quartz - feldspar and epidote, with lesser amounts of biotite and sphene. These rocks are variously deformed. SN. 361 has a vary weak fabric from the alignment of slightly elongate hornblende up to 1 mm long, occurring with rounded fine grained epidote and polygonal quartz and feldspar. The rock is fairly homogenous throughout (plate 8.3.C). SN. 371 is similar, but with a slightly stronger fabric, from the alignment of amphibole. There is also a weak layering parallel to this fabric of amphibole rich and poor layers. Epidote is more coarse grained than in SN. 361, and is generally zoned. Quartz and feldspar tend to be rounded or elongate, but not polygonal. SN. 423 is similar again, but with a strong fabric. There is much epidote and less quartz and feldspar in this particular sample. Amphibole is fine grained, up to 0.2 mm across. Skeletal sphene occurs, growing around quartz, feldspar and epidote. Rare biotite also occurs. This particular sample is cut by feldspar - stilpnomelane - filled cracks, although most are cut by brittle K - feldspar filled cracks (plate 8.7.C). Some rocks occur with very strong fabrics. SN. 258 consists of extremely fine grained amphibole, quartz and feldspar, all strongly aligned. The rock is layered with almost pure quartz layers up to 1 mm across occurring between amphibole - quartz - feldspar layers. In these quartz rich layers the quartz is either polygonal or else slightly elongate. Large porphyroblasts of kinked dark brown biotite up to 2 mm across occur. These contain layers of quartz inclusions parallel to the layering outside the biotite, but this fabric also partly wraps around the biotite (plate 8.3.D). SN. 257 is similar, but is amphibole rich and contains both amphibole and biotite porphyroblasts. Quartz and feldspar do not occur within the fabric, but as rounded patches up to 1 mm across of serrated, strained crystals, with occasional fine amphibole crystals.

Other similar rocks occur with varying proportions of biotite and epidote. SN. 452 is far more amphibole rich, and has a foliation cut by feldspar - filled cracks, which are themselves cut by brittle faults of quartz, feldspar and broken amphibole. SN. 459 is sphene rich, and cut by feldspar - chlorite cracks.

Folded versions of these rocks show similar features to unfolded ones. SN. 144 is a schistose rock similar to SN. 258, consisting of elongate amphibole and quartz - feldspar - epidote layers. These have been microfolded (crenulated), with the development of a weak crenulation cleavage (plate 8.4.A). The rock has later been cut by feldspar - stilpnomelane cracks. SN. 140 contains amphibole rich layers, of coarse interlocking amphibole crystals up to 2 mm across within fine grained amphibole - epidote - quartz - feldspar rocks. This sample appears to have been folded twice prior to the intrusion of feldspar - stilpnomelane veins (plate 8.7.D).

8.3.2 Biotite - rich amphibolite

A few of the western Lewisian rocks are biotite rich, rather than amphibole rich, but otherwise they show similar textures and associations as the plagioclase - amphibolites described above.

SN. 449 consists mostly of blades of fox red biotite up to 0.5 mm across with knots of tiny sphene crystals up to 0.25 mm across, and occasional pale green amphibole, up to 0.5 mm across. The rest of the rock consists of quartz and feldspar of variable size, up to 1 mm across, and slightly elongate. Patches of polygonal quartz and dusty feldspar exist (plate 8.4.B). SN. 374 is similar, but contains large amounts of zoned epidote, up to 0.1 mm across.

SN. 246 is a pod of biotite rich rock that consists of huge rounded, strained plates of green biotite up to 5 mm across, full of small inclusions of zoned epidote. The matrix between these porphyroblasts consists of epidote - quartz - calcite, with a weak fabric that wraps about the biotite (plate 8.4.C).

8.3.3 Quartz - feldspar - mica rocks

Amphibole poor, quartzo - feldspathic rocks are rare within the Western Lewisian. They occur surrounding and enveloping basic material rich in amphibole in rare relatively undeformed pods and as occasional thick bands within the schistose amphibolite. The former consist mainly of dusty polygonal plagioclase crystals up to 1 mm across with tiny crystals of zoisite, opaques, biotite and muscovite both as inclusions and at grain boundaries. There are also patches of clean quartz up to 1.5 mm across of smaller strained quartz grains with sutured margins. Rare dark green amphibole occurs as subhedral crystals up to 0.5 mm across, sometimes with tiny quartz inclusions.

Other varieties include a garnet - bearing rock from the Sandaig islands and garnet - free folded and schistose rocks.

At GR 768146, on the Sandaig islands, quartz - feldspar - white mica - epidote or garnet rocks with large euhedral, randomly oriented hornblende are exposed. The rock is crudely banded into quartz - feldspar - white mica - epidote bands, and epidote or garnet - quartz - hornblende bands. Quartz and feldspar occur throughout as large polygonal crystals which are usually unstrained. Small flakes of white mica and tiny aggregates of epidote occur between these crystals. In SN.'s 107 and 108 quartz and white mica occasionally form rectangular pseudomorphs after feldspar, surrounded by tiny epidote crystals (plate 8.7.B). The epidote (in SN. 107) or garnet (in SN. 108) rich bands carry a strong fabric (plate 8.3.A). In SN. 108, the garnet is sometimes partly replaced by epidote. This always occurs with a decrease in grain size, from large anhedral garnet, up to 2 mm across, to fine grained aggregates of garnet and quartz with grains up to 0.1 mm across, to extremely fine grained epidote aggregates replacing garnet. In places pseudomorphs of fine grained epidote aggregate after large garnet occur, surrounded by the finer grained material. Small, euhedral, inclusion free garnets occur randomly throughout the epidote material. Large random hornblendes up to 1 cm long occur, predominantly in the epidote - garnet layers. These contain cores with many fine inclusions of quartz and either epidote or garnet, and have rims that are generally inclusion free.

Garnet - free, deformed rocks predominantly consist of polygonal plagioclase with quartz and biotite, segregated into clean quartz patches and dusty plagioclase - biotite patches, but also with clots of epidote and layers of epidote, sphene and chlorite that are smeared out, and which outline a fabric within the rocks that has been folded (e.g. SN. 1) (plate 8.4.D).

8.3.4 "Amphibolitites"

Amphibole rich rocks consisting almost entirely of amphibole, with rare biotite and very rare epidote, sphene, quartz and apatite occur throughout the western Lewisian, usually as nodules within deformed versions of other amphibolites. They can be divided into hornblendic and actinolitic types, both of which show deformed and undeformed varieties. There are rare occurrences of rocks containing both amphibole and actinolite.

SN. RC1 is a typical hornblendic rock. It consists of dark green interlocking hornblende crystals 1 - 2 mm across. The rock has a weak fabric from the alignment of occasional elongate amphibole crystals up to 3 mm long. The rock is cut by brittle fractures filled by feldspar (plate 8.8). Other samples, such as SN. 370 have abundant sphene occurring as small rounded crystals up to 0.1 mm across between the hornblende crystals. Occasionally these have cores of ilmenite. SN.'s 424 and 425 contain biotite epidote, quartz and apatite between the amphibole grains. All of these are rare, and occur no larger than 0.2 mm across. Biotite tends to be elongate, epidote and apatite rounded, and quartz polygonal, occasionally in aggregates up to 0.75 mm across. SN. 373 has a much stronger fabric with many of the amphiboles up to 3 mm long and aligned. SN. 364 is extremely fine grained, with tiny amphibole up to 0.05 mm long, with inclusion free porphyroblasts of similar amphibole occurring on all scales up to 2 mm across growing over the fabric. Rare biotite porphyroblasts occur (plate 8.5.A). A few narrow quartz bands with slightly coarser grained quartz and amphibole occur.

Actinolitic rocks occur in a similar variety to those above, with or without biotite and quartz. Often the rocks have a weak fabric from the alignment of long actinolites. SN. 429 is typical, consisting entirely of long thin crystals of amphibole up to 5 mm long. It is cut by brittle cracks filled by quartz and feldspar (plate 8.5.B).

SN. 367 is a unique actinolitic rock consisting of actinolite and chlorite. The actinolite occurs as large interlocking rectangular crystals 4 - 5 mm long and 1 - 2 mm across, all of which are zoned in concentric layers up to 0.1 mm thick parallel to the edges of the crystals. Chlorite occurs as fine grained aggregates filling the gaps between actinolite crystals (plate 8.5.C).

Two samples, SN. 432 and SN. 456 contain both hornblende and actinolite. The amphibole crystals tend to be up to 3 mm long and generally have cores of dark green hornblende and rims of pale green actinolite. Biotite is common, occurring as dark green laths up to 1 mm long. In SN. 456 the amphibole is sometimes more patchy with seemingly random distribution of dark hornblende and pale actinolite (plate 8.6.A). SN. 432 is cut by a thick quartz - feldspar - calcite - chlorite filled crack containing needles of actinolite.

8.3.5 Summary

Only garnet - amphibolite and plagioclase - amphibolite show evidence of any textures similar to those seen in the eclogites, i.e. seive amphibole after pyroxene, amphibole - epidote intergrowths after garnet, plagioclase - chlorite symplectites and rutile. It is thus inferred that the garnet - amphibolites and plagioclase - amphibolites are related to the eclogites, but that "amphibolitites" are not because they do not have similar textures. A few "amphibolitites" show cross - cutting relations with the plagioclase - amphibolites (chapter seven), it seems likely that these rocks were intruded into the other Western Lewisian rocks. At high pressure and temperature the amphibolitites may not ever have contained jadeite - rich clinopyroxene or garnet, due to their bulk chemistry, and hence would not be expected to show textures similar to retrogressed eclogites, thus the absence of such textures is not indicative of their not having been to eclogite facies. However, the possibility that these rocks may not have seen eclogite facies metamorphism is discussed in section 6.7.4 and 7.3.

In chapter seven five deformation events were described, D_0 - D_4 after May *et al.* (1993, chapter two). D_0 is not readily identified in thin section. D_1 forms a strong fabric in many of the rocks and is possibly responsible for forming pods of massive rocks within deformed schists. There are both D_2 folds and strong fabrics, the folding often as tight crenulations with an associated cleavage. Later folds of D_3 affect most of the rocks.

Garnet porphyroblasts within garnet - amphibolites appear to overgrow an early fabric but are apparently wrapped by a later fabric. Garnet within SN.'s 107 & 108 shows evidence for the initial breakdown of garnet to epidote and ilmenite with deformation, prior to the re - growth of garnet after strong deformation. A similar situation occurs in SN. 1, but without the regrowth of garnet. The strong deformation overgrown by garnets is probably D_2, by correlation with garnet - free folded and schistose rocks, and the garnet breakdown is pre - or syn - D_1. Barber and May (1975) also suggested that the peak of metamorphism was immediately post D_2.

The two most common amphibolite types, the plagioclase - amphibolite and the "amphibolitite" both show evidence of similar histories, with coarse randomly oriented, or weakly foliated rocks forming pods within deformed equivalents. These deformed versions show a similar range of textures, including strongly deformed fine - grained rocks, with the growth of late porphyroblasts of amphibole or biotite. In SN. 246, a unique biotite rock, there are large biotite porphyroblasts.

8.4 Granulites north of Loch Duich & Loch Alsh

These rocks were briefly described in thin section by Barber and May (1975). Two samples were obtained from the north coast of Loch Duich, alongside the A87, but both are strongly retrogressed. SN. 306 is a garnet - amphibole - plagioclase rock. Relicts of garnet occur, altered along cracks and at grain rims to amphibole and to epidote - plagioclase symplectites. Hornblende occurs full of tiny inclusions of quartz and ilmenite and probably therefore occurs after pyroxene. Plagioclase is always full of tiny lathes of zoisite. Dirty sphene occurs throughout, usually with cores of rutile. SN. 324 is a quartz rich rock with garnet - quartz - plagioclase - biotite - ilmenite. The garnet is dark pink, and occurs either as large anhedral crystals up to 1.5 mm across or as finer grained polygonal crystals, generally about 0.2 mm across. Deep brown biotite occurs as patches of coarse crystals up to 1.0 mm across. Otherwise, that rock is fairly fine grained and consists mostly of quartz and plagioclase. Small euhedral crystals of ilmenite and pyrite occur throughout along with tiny elongate amphiboles, usually around garnet crystals.

8.5 Moine Rocks

The Moine occurs as a thin, highly deformed strip within the Western Lewisian succession and to the west of the succession where they overlie the Lewisian with a basal unconformity (Peach *et al.*, 1910). The highly deformed strip is a quartz - feldspar - biotite - muscovite schist with lathes of both micas up to 0.5 mm long outlining the fabric. The Moine to the west of the Lewisian is a garnet bearing schist. Garnet, biotite and muscovite all occur as large porphyroblasts up to 5 mm across that occur in a foliated rock. The garnets have grown over crenulations on the foliation. Randomly oriented, elongate porphyroblasts of chlorite and calcite occur throughout. These pseudomorph earlier crystals that have typical euhedral amphibole shapes, and are assumed to be remnants of amphibole (plate 8.6.B).

8.6 Conclusions

Petrological examination of the rocks suggests that many plagioclase - amphibolites within pods, including the migmatites, contained textures compatible with their being retrogressed eclogites, i.e. sieve amphibole with quartz inclusions and rutile cores to sphene. The presence of large quantities of quartz - feldspar in the migmatites may well be the equivalent of QFK streaks within the Eastern Lewisian rocks. The Western Lewisian eclogites themselves are broadly similar to the Eastern Lewisian eclogites, but they contain much higher quantities of plagioclase - biotite - (amphibole) intergrowths and have no direct evidence of QFK streaks.

Pods of "amphibolitites", whether actinolitic or hornblendic, contained only coarse amphibolite, with no evidence of earlier high - pressure mineralogy, such as sieve - amphibole after clinopyroxene. Coupled with the cross - cutting field evidence (chapter seven), these rocks are almost certainly later intrusions into the early eclogitic (possibly partly retrogressed) metabasic rocks. The only other texture seen within the "amphibolitites" is in SN. 267 which has a pseudo - igneous texture.

D_1 deformation appears to have formed a strong fabric in many of the rocks, although some pods, the eclogites and amphibolites of all types, are massive and the pods were probably formed during D_1. During D_2 many of the rocks were deformed to produce a strong schistosity, which in many cases is crenulated. Evidence in some rocks suggests that garnet broke down to form epidote and sphene (or ilmenite), before later regrowth. The breakdown of garnet must have occurred pre - or syn - D_1 as layers of epidote - ilmenite/sphene after garnet are smeared out and outline the D_1 foliation in many of the rocks. As suggested by previous workers, e.g. Ramsay (1957), regrowth of the garnet was post - D_2, along with the growth of large biotite and hornblende crystals in many of the rocks of all types, including the Moine, assumed to be the peak of post Moine deposition metamorphism.

Many of the rocks, particularly the pods, are cut by either epidote - actinolite or K - feldspar filled cracks, similar to those across the eclogites of the Eastern Lewisian, of D_3 age. Most rocks, both pods and the country rocks are cut by cracks, predominantly filled by K - feldspar, but also other minerals, often stilpnomelane. These cracks usually contain broken fragments of amphibole from the surrounding rock, indicating some sort of late brittle deformation, similar to that seen in the Eastern Lewisian, interpreted as being D_4.

The few cracks that do occur across the eclogites are similar to those in the Eastern Lewisian, filled by amphibole - plagioclase and by epidote - actinolite respectively. Correlation between cracks across the eclogites and those across other Western Lewisian rocks is uncertain.

Plate 8.1.

A) Eclogite from pod centre (SN. 252). Broken garnet (pink) and clinopyroxene (green) with much quartz and rutile (dark). Minor alteration of clinopyroxene to a fine symplectite (dark). Patches of biotite - plagioclase symplectite (blotchy brown) with brown biotite and dusty plagioclase. (field of view : 7 mm).

B) Eclogite from pod centre (SN. 418). Garnet (pink) and clinopyroxene (pale green) with dark green amphibole and quartz. (field of view : 4 mm).

C) Partly retrogressed eclogite with unaltered garnet (pale), brown amphibole, quartz and symplectite after clinopyroxene (dark, messy) (SN. 410). (field of view : 9 mm).

D) Vein of actinolite - epidote cutting eclogite (SN. 356). Brown amphibole at vein rim is replaced by actinolite. (field of view : 3 mm).

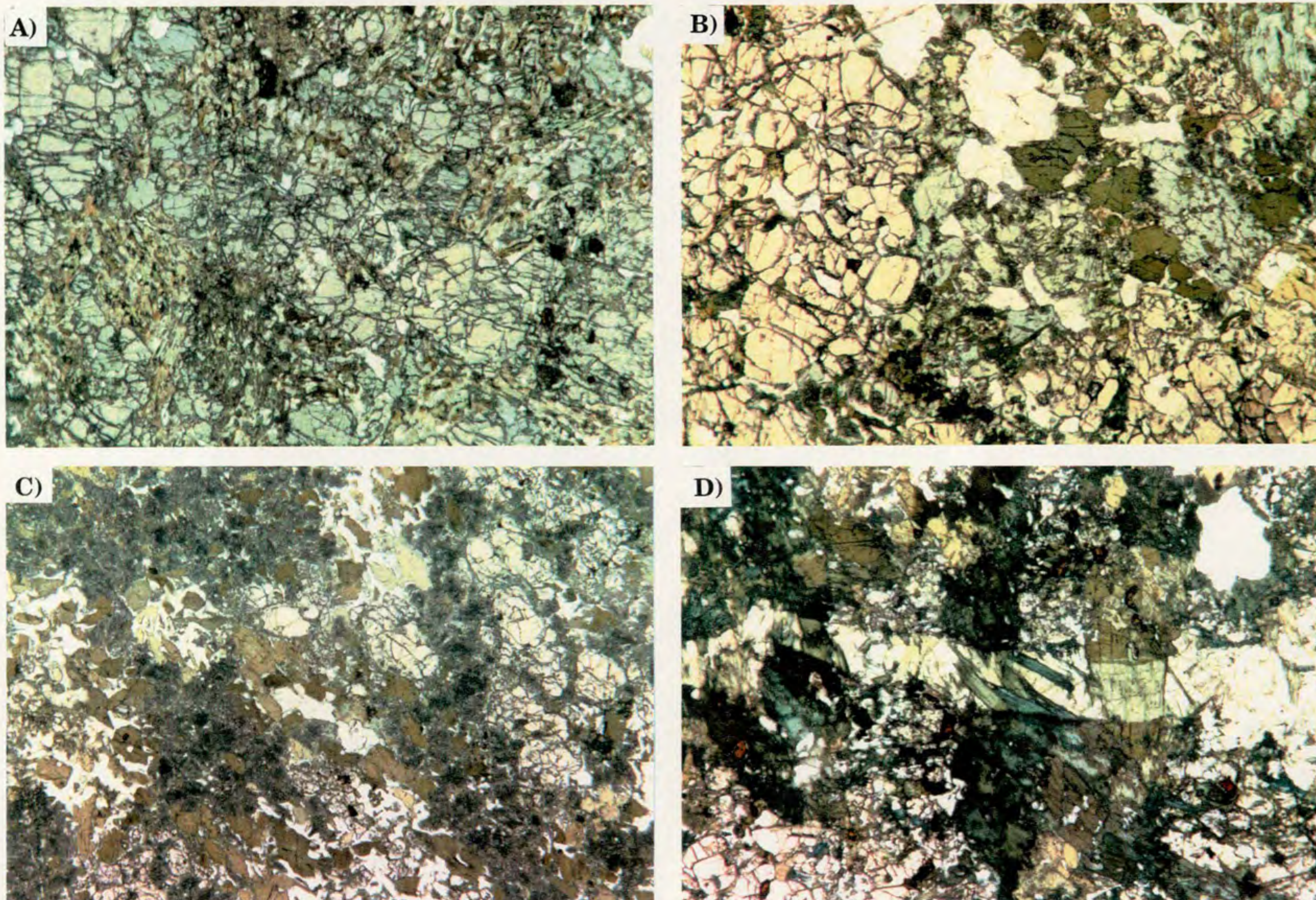

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Plate 8.2.

A) Altered eclogite from close to pod rim (SN. 415). Patches of quartz and biotite - plagioclase symplectite (left) and of altered eclogite (right) with garnet altered to epidote - plagioclase - amphibole intergrowths and clinopyroxene to amphibole with quartz inclusions. (field of view : 6 mm).

B) Retrogressed eclogite from pod rim (SN. 414). Quartz rich, with amphibole and epidote - plagioclase intergrowths after eclogite and chlorite after biotite in symplectite with dusty plagioclase (brown). (field of view : 5 mm).

C) Detail of epidote within a garnet - amphibolite (SN. 402) at an eclogite pod rim. Epidotes have clean core, inclusions rich overgrowths, then clean overgrowths. (field of view : 1 mm).

D) Garnet within garnet - amphibolite (SN. RC2). Garnets contain a fabric outlined by sphene and quartz inclusions, oblique to the fabric in the surrounding amphibolite, composed of amphibole, biotite, plagioclase and quartz. (field of view : 9 mm).

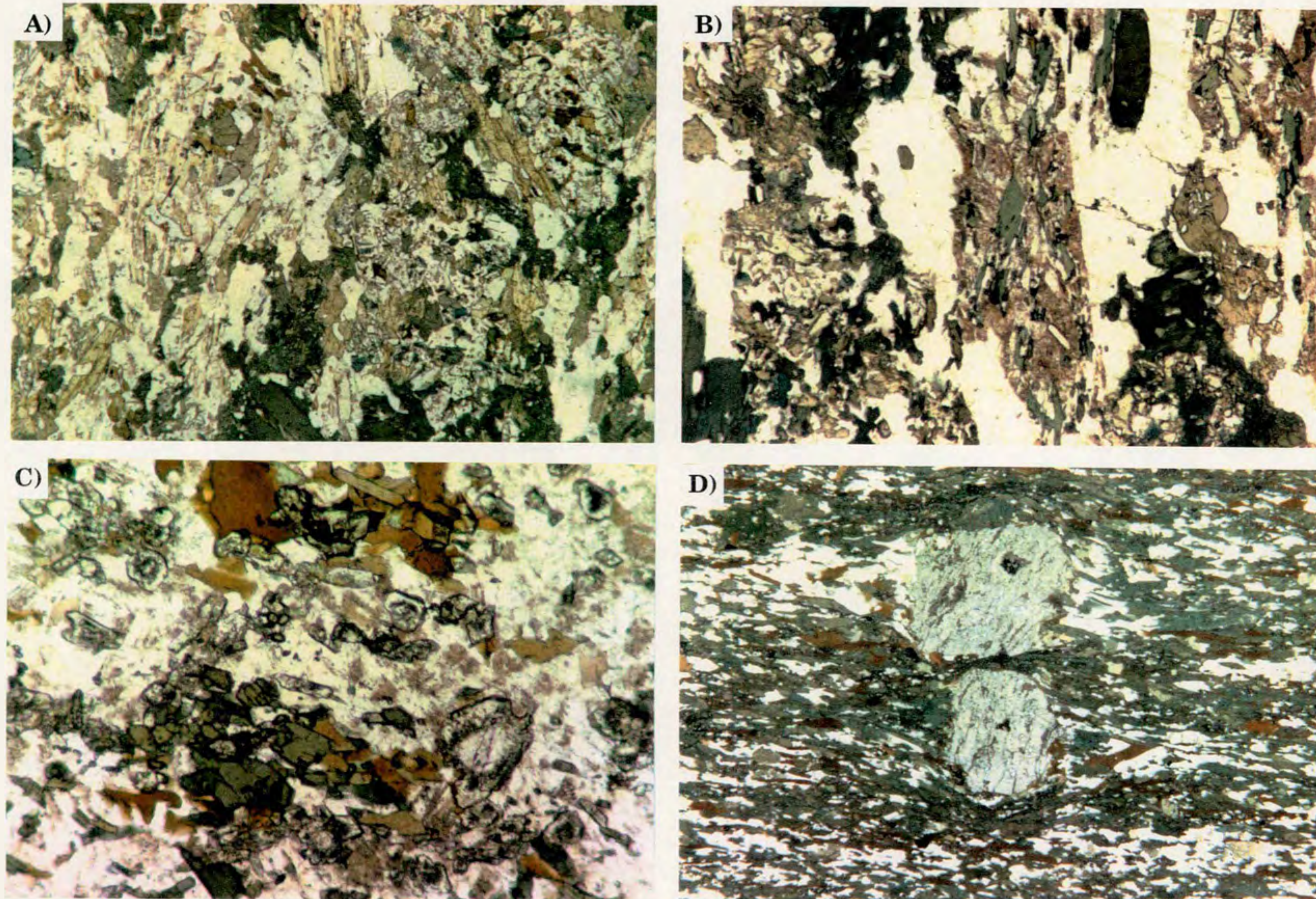
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Plate 8.3.

A) Quartzo - feldspar rich garnet - amphibolite (SN. 108). Fine fabric of quartz, feldspar and epidote (brown) is overgrown by coarse randomly oriented, euhedral amphibole and tiny euhedral garnet (pale, high relief). (field of view : 9 mm).

B) Plagioclase - amphibolite pod (SN. 359). Coarse amphibole with or without quartz, possibly after clinopyroxene, clots of quartz, epidote - plagioclase - amphibole intergrowths, possibly after garnet. (field of view : 9 mm).

C) Typical plagioclase - amphibolite with amphibole outlining a weak fabric, relict coarser amphibole with quartz inclusions, epidote, plagioclase and quartz (SN. 361). (field of view : 12 mm).

D) Strongly deformed plagioclase - amphibolite with large poikiloblasts of biotite overgrowing the fabric (SN. 258). (field of view : 11 mm).

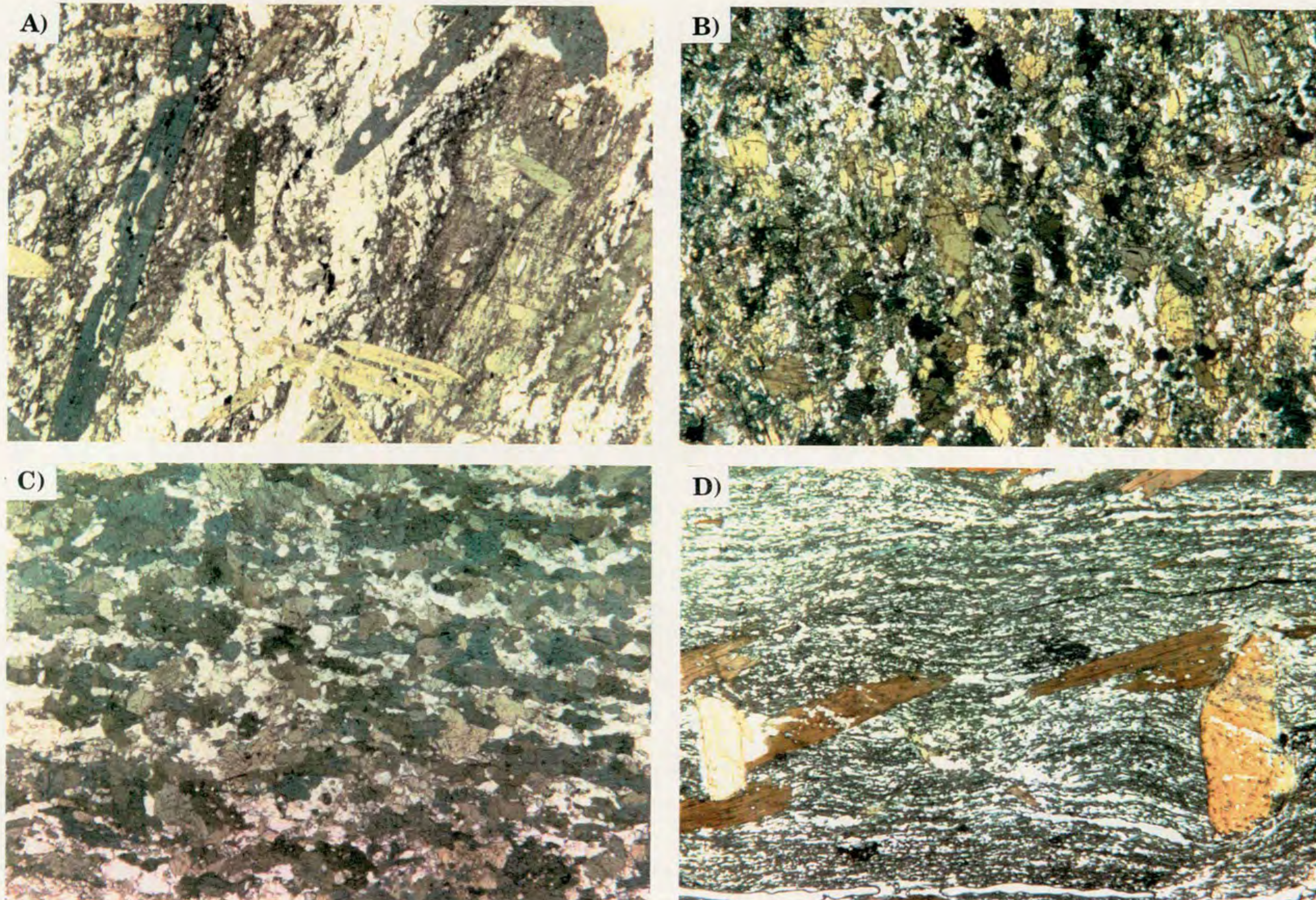
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Plate 8.4.

A) Deformed plagioclase - amphibolite (SN. 144). Strong fabric within amphibolite is crenulated with crenulation cleavage developing. (field of view : 10 mm).

B) Typical biotite - amphibolite with biotite - amphibole - plagioclase - quartz (SN. 449). Biotite is elongate defining the schistosity. Amphibole is usually rounded with quartz inclusions. (field of view : 9 mm).

C) Biotite - epidote - plagioclase - calcite pod with coarse biotite growing over zoned epidote, with inclusion rich cores and inclusion free rims (SN. 246). Biotite has probably grown syn - deformation as it is partly wrapped by and partly overgrows fabric. (field of view : 6 mm).

D) Quartzo - feldspathic amphibolite with strong fabric outlined by layers of epidote (brown) and sphene (black), partly folded parallel to the fabric (SN. 1). The bulk of the rock is biotite (brown) - quartz and feldspar. (field of view : 15 mm).

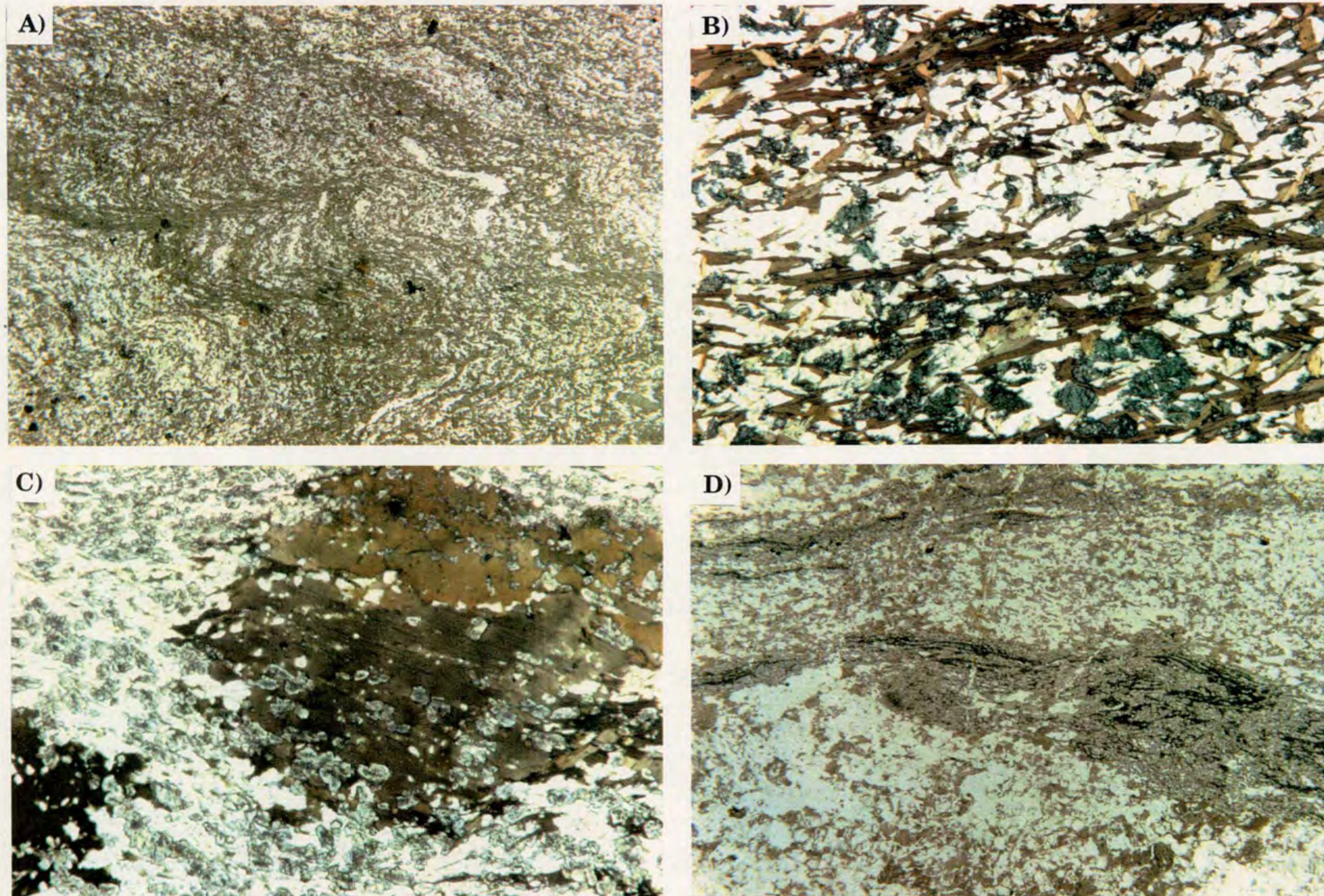
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Plate 8.5.

A) Strongly deformed "amphibolitite" with rare biotite (SN. 364). Large porphyroblasts of amphibole overgrow the fabric. (field of view : 14 mm).

B) Deformed actinolite - biotite "amphibolitite" (pale areas are holes in the slide) with fabric outlined by elongate crystals (SN. 429). Cut by brittle cracks filled with K - feldspar. (field of view : 14 mm).

C) "Amphibolitite" of coarse actinolite with interstitial chlorite (SN. 267). Actinolites are zoned parallel to the crystal edges and are generally euhedral. (field of view : 12 mm).


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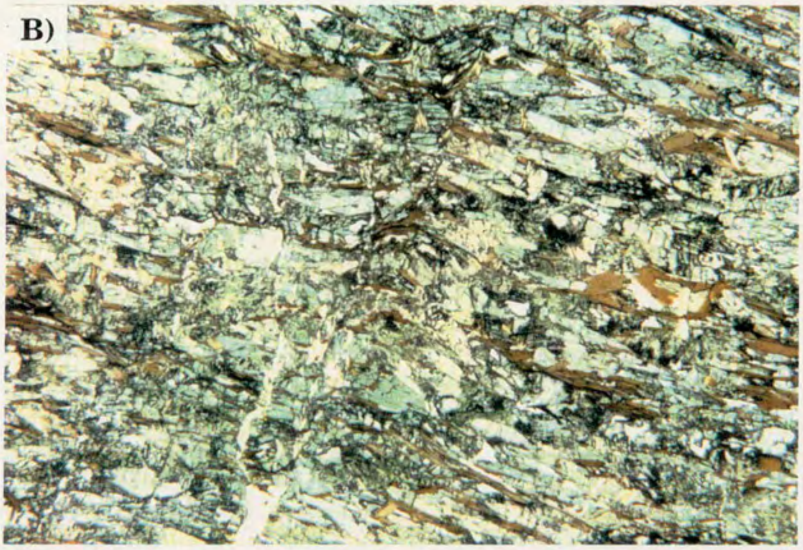
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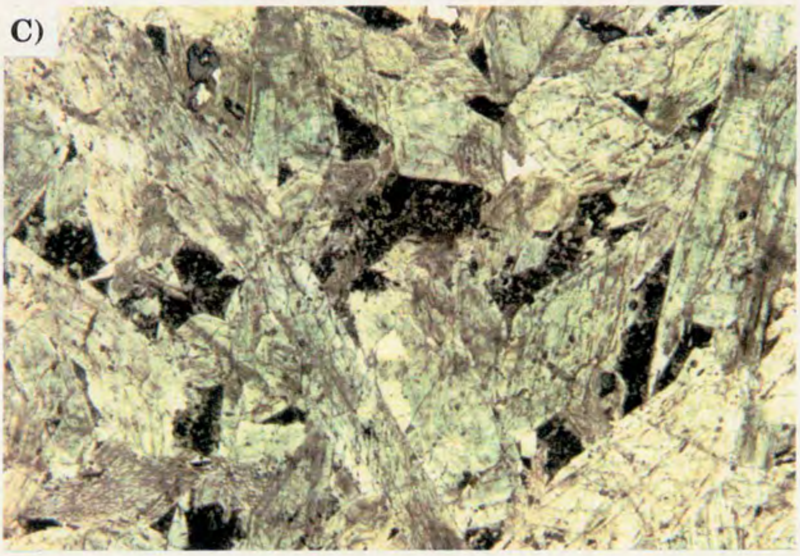
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Plate 8.6.

A) "Amphibolitite" with amphibole and biotite (pale areas are holes in the slide) (SN. 432). Biotite outlines a weak fabric. Amphibole is both hornblende (dark green) and actinolite (pale green). Usually the actinolite occurs at the rims of amphibole crystals. (field of view : 5 mm).

B) Moine pelite with coarse poikilitic, euhedral garnet (grey), biotite (brown) and possibly amphibole (green) (SN. 100). The latter is now replaced by calcite and chlorite. All three overgrow a strong fabric defined by muscovite. (field of view : 12 mm).

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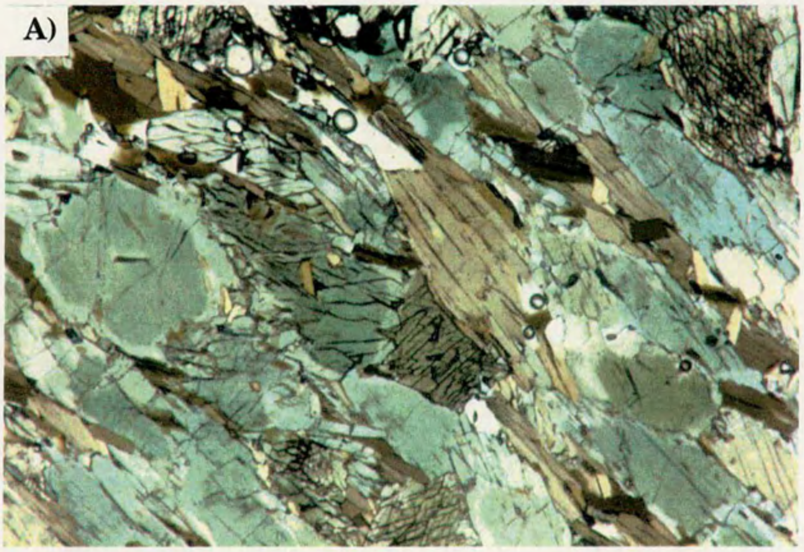

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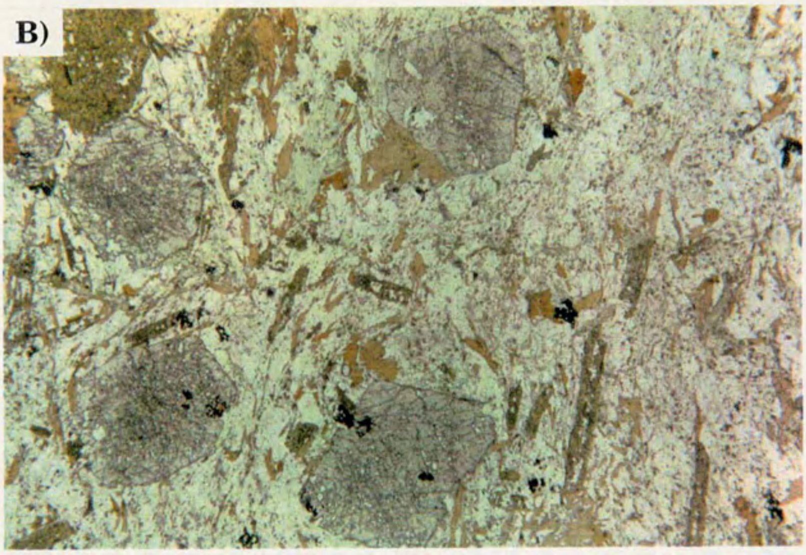

Plate 8.7.

A) (in crossed - polars) Eclogite (SN. 420) with plagioclase (white) rimming quartz and garnet (both black). (field of view : 1 mm).

B) Quartz - feldspar rich garnet amphibolite (SN. 108) (see plate 8.3.A). Quartz - epidote - muscovite - plagioclase rich patches (pale) and epidote - quartz - amphibole patches (dark). Some relict euhedral K - feldspar pseudomorphs occur (e.g. left centre) replaced by muscovite and quartz. (field of view : 25 mm).

C) Plagioclase - amphibolite with strong fabric cut by K feldspar filled cracks (top - bottom), that are offset by microfaults (left - right) with milled amphibole and plagioclase (SN. 452). (field of view : 12 mm).

D) Folded plagioclase - amphibolite (SN. 140). Coarse interlocking amphibole layer within fine grained plagioclase - amphibolite is possibly the core to an early fold, now refolded. (field of view : 15 mm).

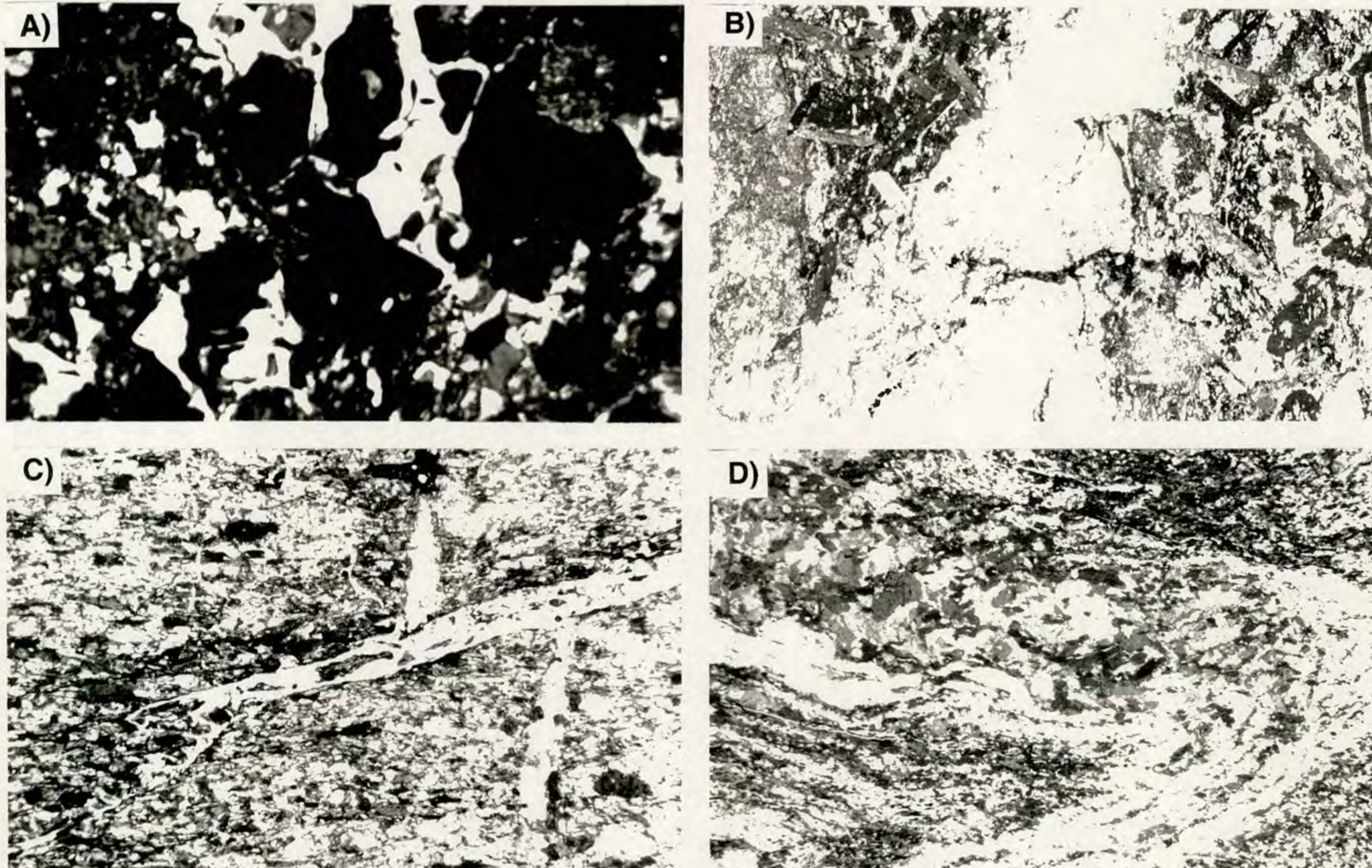
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Plate 8.8.

"Amphibolitite" of randomly oriented hornblende (pale areas are holes in the slide) cut by narrow K - feldspar filled cracks (SN. RC1). (field of view : 14 mm).

Chapter Nine

Geochemistry of the Western Lewisian rocks

CHAPTER 9

Geochemistry of the Western Lewisian rocks

9.1 Introduction

In chapter eight the Western Lewisian rocks were separated into five groups dependant upon their mineralogy: eclogite, garnet - amphibolite, plagioclase - bearing amphibolite, biotite - rich rock, and amphibolitic rocks consisting mostly of pure amphibole, termed "amphibolitites" (both hornblendic and actinolitic varieties occur). These categories have been used as a basis for examining the bulk compositions of the rocks. The Western Lewisian eclogites have a similar textural history to those of the Eastern Lewisian. Some of the amphibolites appear to have a similar textural history to retrogressed versions of the eclogites. Other amphibolites, the "amphibolitites" have different textures and were interpreted as being intruded into the Western Lewisian after eclogite facies metamorphism (chapter seven).

In this chapter the whole rock chemistry of the Western Lewisian rocks will be presented and compared with the textural evidence from the previous chapter in order to determine whether some metabasic rocks within the Western Lewisian are fundamentally different to others. The mineralogy will also be discussed. Major and minor element whole rock analyses were obtained by XRF. Major element mineral analyses were obtained using an electron microprobe, whilst limited trace element mineral analyses were obtained using an ion microprobe. Analytical procedures are described in appendix II. Whole rock analyses and representative mineral analyses are given in appendix III and IV.

All plots of mineral analyses for any one rock type contain more than one analysis from each sample analysed, often with more than one analysis from any one grain. For major element analyses, 9 samples were used for the eclogite, 5 samples for garnet - amphibolite, 12 for the plagioclase - amphibolite, 3 for biotite - rich rock and 11 for the "amphibolitites".

9.2 Whole Rock Chemistry

9.2.1 Major element chemistry

CIPW Norm. calculations show the Western Lewisian eclogites to be quartz - normative tholeiitic basalts. The garnet amphibolites are similar, but the samples analysed contain much higher TiO_2 contents. The plagioclase - amphibolites show a wide variety of compositions from quartz - normative to olivine - normative. The "amphibolitites" are all olivine - normative rocks. Figure 9.1 - 3. A garnet granulite from north of Loch Duich (SN. 306) is slightly different to the eclogites, being SiO_2 poor, but in general all rocks apart from the "amphibolitites" have $Al_2O_3 \geq Fe_2O_3$ and $MgO < CaO$, whilst the "amphibolitites" have $Al_2O_3 < Fe_2O_3$ and $MgO \geq CaO$.

9.2.2 Minor element chemistry

The largest difference in minor element bulk chemistry between the different Western Lewisian rock types is Cr content. The "amphibolitites" have high Cr content, greater than 1200 ppm, whilst all the other rock types have low Cr content, usually below about 500 ppm, figure 9.4. There is a similar difference in Ni content, with the "amphibolitite" having over 350 ppm, and all the other rocks having less than 200 ppm. In general the Western Lewisian eclogites are richer in most trace elements than the Eastern Lewisian eclogites, including all the mobile elements such as K, Rb and Nb. Cr is the main exception.

9.2.3 Summary

Apart from the "amphibolitites", the rocks of the Western Lewisian all have broadly similar major element chemistry, ranging from quartz - normative to olivine - normative tholeiites. The "amphibolitites" are high Mg, Cr, and Ni rocks, that were presumably fairly ultrabasic, were it not for the high SiO_2 content. They appear to plot on different trends to the other rocks of the Western Lewisian and therefore may well be unrelated to them.

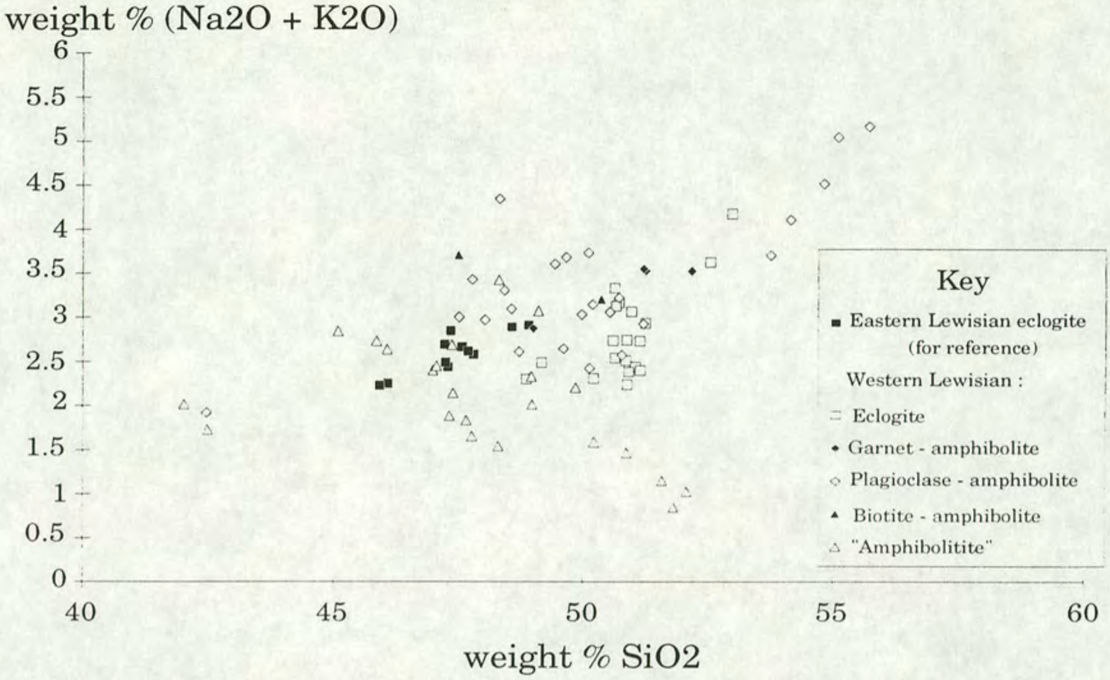

Figure 9.1 Total alkali - silica plot for Western Lewisian rocks. All rock types identified in chapter 8 apart from the "amphibolitites" lie on a tholeiitic trend. Many of the "amphibolitites" lie off this trend with decreasing SiO_2 as alkalis increase. The Eastern Lewisian bimineralic eclogites are plotted for reference, and are silica poor compared to the Western Lewisian.

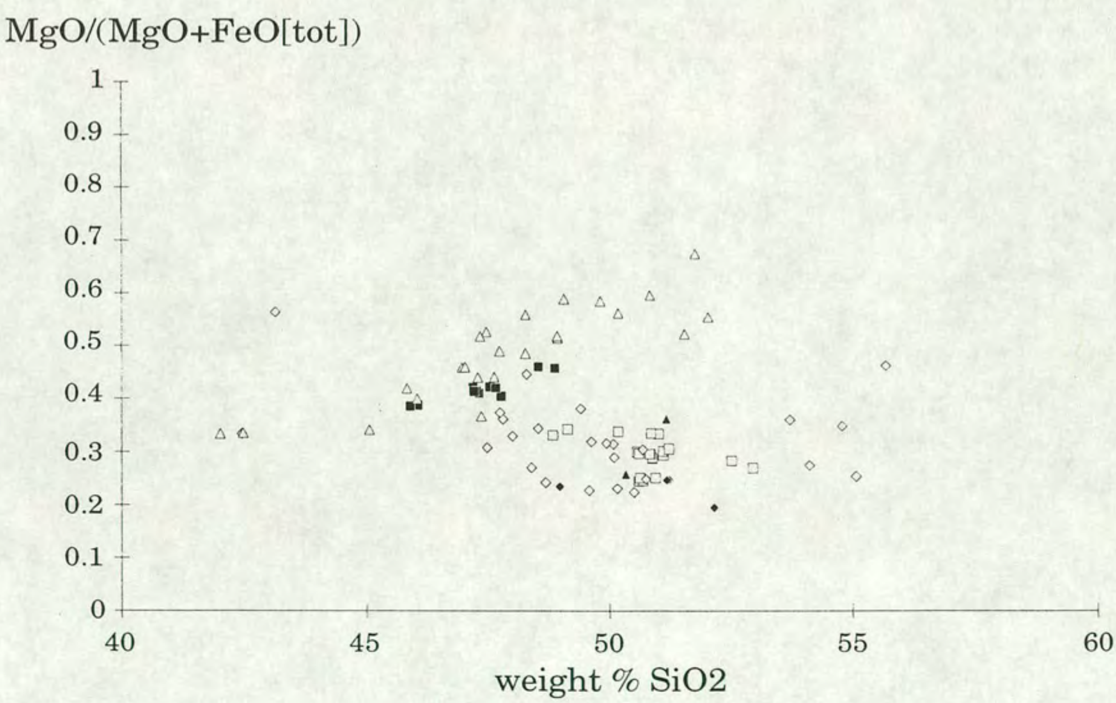

Figure 9.2 Whole rock compositions of Western Lewisian rocks. (Symbols as in figure 9.1) The "amphibolitites" have Mg no. rising with increasing silica, unlike the other rocks that have a fairly constant Mg no.

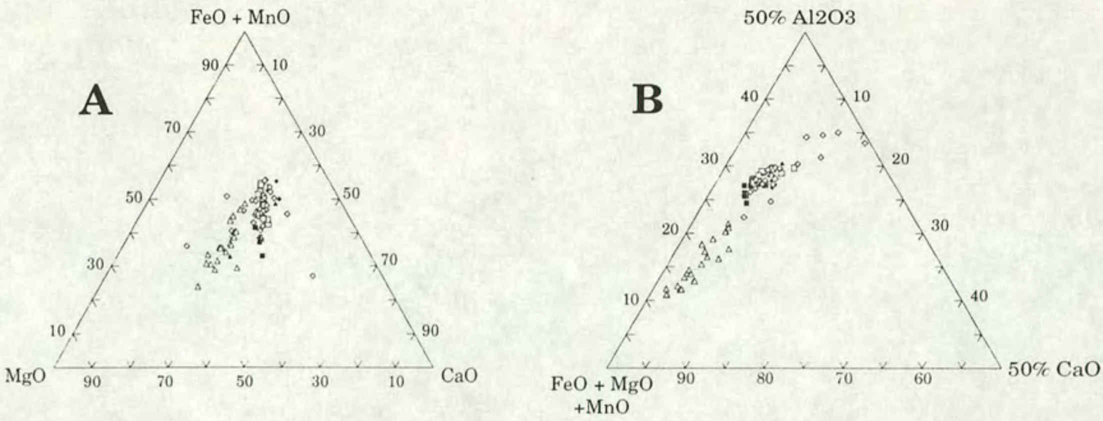

Figure 9.3 Whole rock compositions of Western Lewisian rocks. (symbols as in figure 9.1) **A :** All but the "amphibolitites" lie on the same trend with roughly constant MgO / CaO. The "amphibolitites" are MgO rich and plot on a different trend. **B :** The "amphibolitites" are Al_2O_3 poor, but plot on a similar trend to the other Western Lewisian rocks.

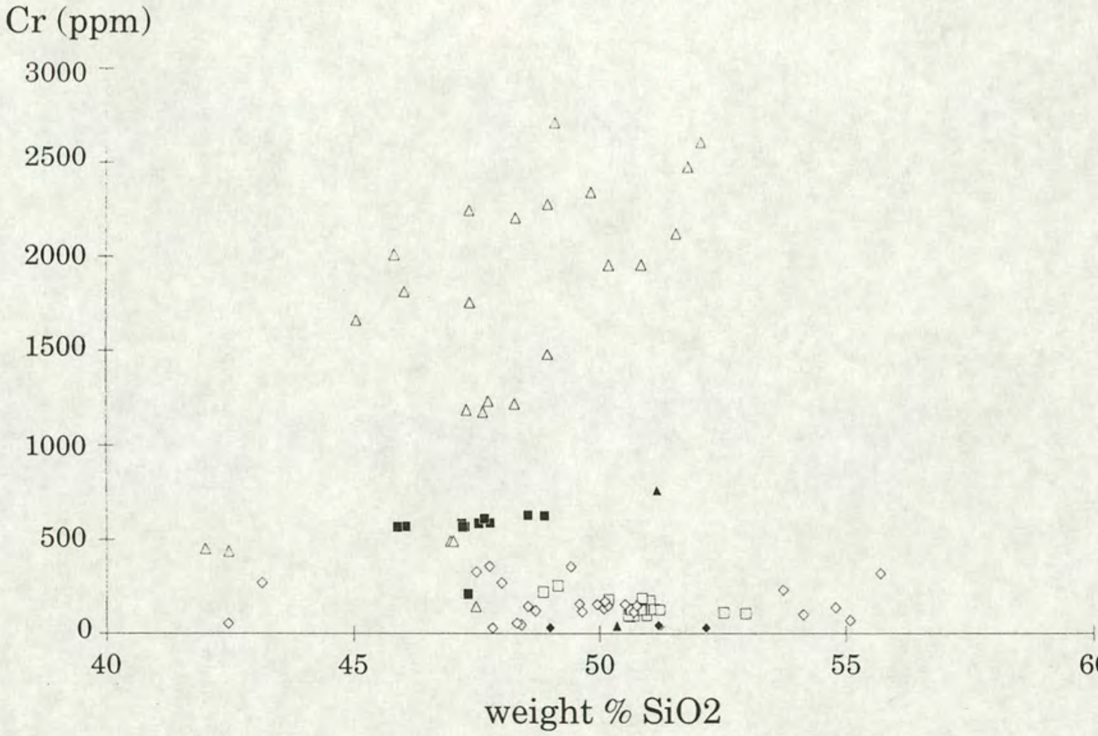

Figure 9.4 Whole rock chemistry of the Western Lewisian rocks. (symbols as if figure 9.1). Cr content of the "amphibolitites" is considerably higher than for any other rock type from the Western Lewisian.

9.3 Mineral Chemistry

9.3.1 Garnet

Garnet occurs with pyroxene in eclogite and with amphibole in rare garnet - amphibolite. Figure 9.5 show profiles across garnets from two eclogites, figure 9.6 a profile across garnet from a garnet amphibolite. All have fairly flat homogenous compositions. The eclogite garnets in particular show enrichment in CaO at crystal rims, at the expense of both FeO and MgO. Garnets from garnet amphibolite are comparatively MnO rich, and CaO rich, FeO poor alongside cracks.

Within the eclogites, garnet is pyrope poor by comparison with the Eastern Lewisian eclogite, with around 15 - 25% pyrope ($Mg_3Al_2Si_3O_{12}$) and 20 - 30% grossular ($Ca_3Al_2Si_3O_{12}$). As with the Eastern Lewisian eclogites, the garnets show a change in both Ca content and Mg no., figure 9.7. Garnets in retrogressed eclogite are generally more iron rich than in relatively unretrogressed eclogite. Garnets from garnet - amphibolite are even more iron rich than those in the eclogite, with only around 10% pyrope end - member. They show a marked change from being Ca - rich to Fe - rich. One sample, SN. 402, a quartz - rich rock from the rim of a completely retrogressed eclogite, is different and has garnets of similar composition to those in the eclogite.

9.3.2 Clinopyroxene

Clinopyroxenes are only found within the eclogites in the Western Lewisian south of Loch Duich. They are of similar composition to that in the Eastern Lewisian eclogites except are slightly more Fe''' - rich[1] (figure 9.8). In general the cores of anhedral crystals in the freshest eclogite have the highest Al_{vi} content, whilst the rims of such crystals tend to have slightly lower values. In rare secondary symplectites of pyroxene with plagioclase there is up to 10% jadeite.

9.3.3 Amphibole

Amphibole occurs throughout the basic rocks of the Western Lewisian. It occurs within the eclogites as a possible primary mineral (similar to those in the Eastern Lewisian eclogites), as alteration products of garnet and pyroxene, and as a crack - filling

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[1] Calculation of clinopyroxene end - member compositions is discussed in section 5.3.3.

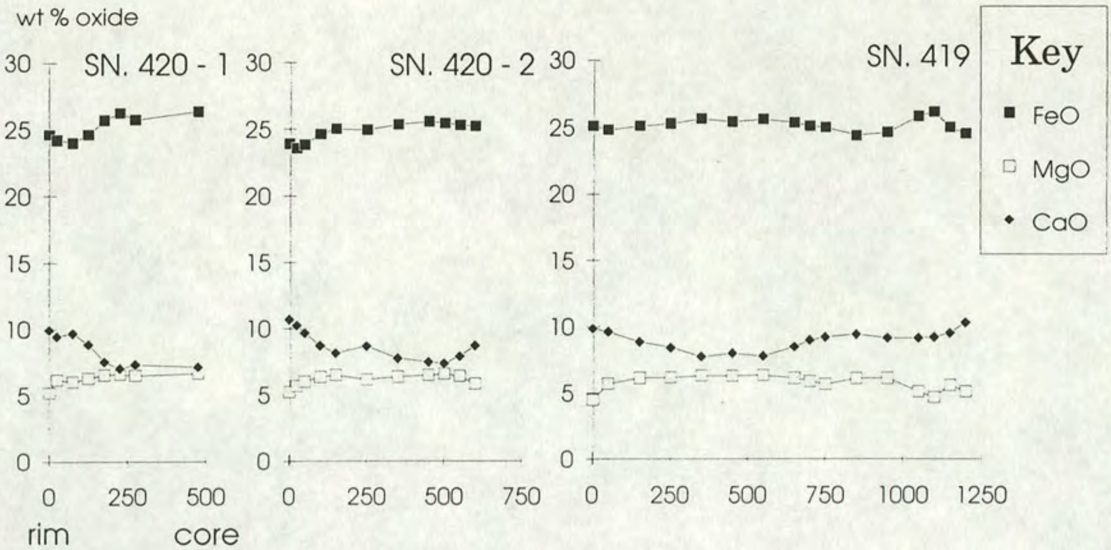


Figure 9.5 Profiles across garnets from two Western Lewisian eclogites. All three garnets show enrichment in CaO at grain rims at the expense of both FeO and MgO. There is little evidence of enrichment in FeO at the expense of MgO seen at the rims of Eastern Lewisian eclogites. The garnet from SN. 419 possibly has a CaO poor core and then a CaO richer composition around that, perhaps similar to SN. 83 in the Eastern Lewisian (figure 5.3)

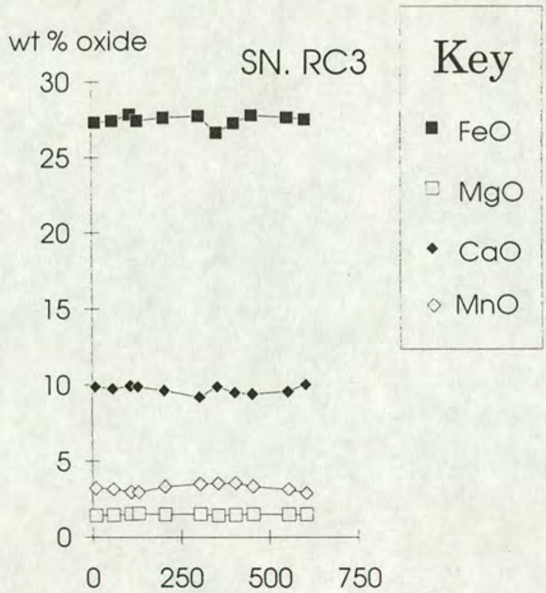


Figure 9.6 Profile across garnet from a Western Lewisian garnet amphibolite. The garnet has a fairly flat profile with slight enrichment of CaO at grain rims at the expense of FeO and MnO. Alongside a crack is a loss of FeO and gain of CaO.

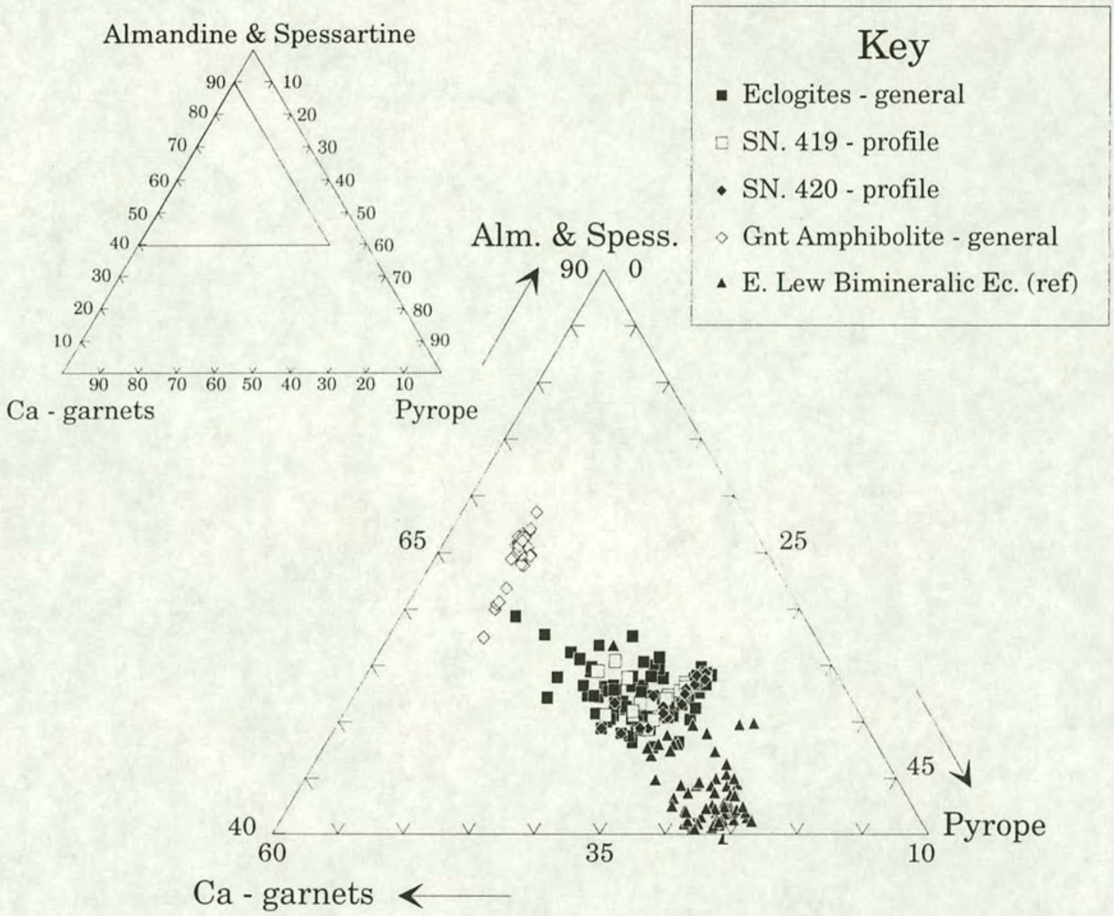


Figure 9.7 End member plot for Western Lewisian garnets. The small triangle shows the location of the main triangle. Bimineralic eclogite garnets from the Eastern Lewisian are plotted for reference. The Western Lewisian eclogite garnets are Mg poor compared to all Eastern Lewisian eclogite types. The profiles show a change in Ca content with fairly constant proportion of Fe and Mg, and a gain in Fe and loss of Mg at fairly constant Ca, for the Ca richer garnets. Garnets from garnet amphibolites are Mg poor, and show a change only in the proportions of Ca and Fe.

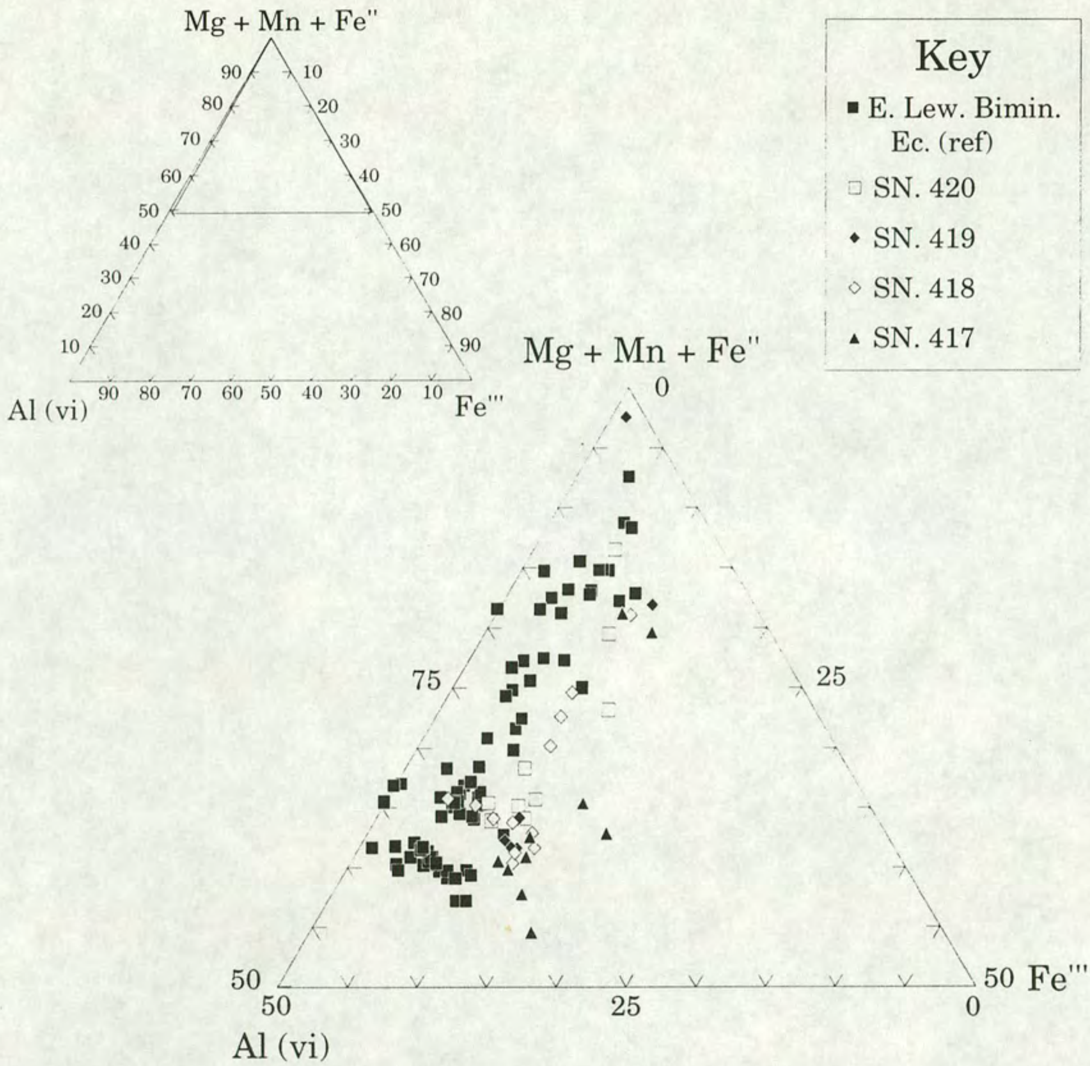


Figure 9.8 MMF - Al_{vi} - Fe''' plot for Western Lewisian clinopyroxenes. The small triangle shows the location of the large triangle. Eastern Lewisian bimineralic eclogite clinopyroxenes are plotted for reference. Western Lewisian eclogite clinopyroxenes are Fe''' rich compared to those from the Eastern Lewisian. They are also slightly poorer in Al_{vi} with comparable amounts to the rims of some Eastern Lewisian bimineralic eclogites. Symplectitic clinopyroxenes are Al_{vi} poor, with similar contents to those of the Eastern Lewisian.

mineral. Outwith the eclogites it is the main constituent of the bulk of the basic rocks. The chemistry of the amphiboles is illustrated in figures 9.9 - 13. Amphiboles within any one sample are of approximately constant composition, except for those in late veins. In general, amphiboles from the "amphibolitites" are more actinolitic than all amphiboles in other rocks from the Western Lewisian, except for rare actinolite within cracks across the eclogite. Amphiboles from the eclogite have consistently higher pargasite contents, lower Mn and lower Mg no. than amphiboles from other rocks. Those from the "amphibolitites" have high Mg no., high Si content and low Na content.

REE compositions of six amphiboles within an eclogite sample (SN. 356) were obtained. These were for hornblende growing from alteration of garnet and pyroxene, for hornblende at the rim of a crack, and for actinolite within a crack. The REE content of the amphibole at the crack rim is similar to that of actinolite growing within the crack, unlike in an Eastern Lewisian eclogite where hornblende at the rim of a vein has REE contents similar to hornblende throughout the rock, figure 9.14.

9.3.4 Other phases

Both **K - feldspar** and **plagioclase** occur within the eclogites, but in other rocks K - feldspar is restricted to veins. K - feldspar is always virtually pure end member composition. Rare albite occurs within the eclogite in symplectites with diopside, after jadeite, but plagioclase in all rocks is mostly An_{12-22} (oligoclase). The "amphibolitites" are plagioclase free. **Biotite** occurs in small quantities in most of the Western Lewisian rocks, and in some cases, the biotite - rich rocks, it forms the main ferromagnesian mineral. Biotite in all rocks, including minor biotite in "amphibolitites" is of fairly restricted composition, with about 2 weight % TiO_2, although it is a little higher in the eclogites. The Mg no. of biotite is about 0.55 - 0.65, although this is sometimes higher in the "amphibolitites". **Chlorite** growing after biotite in the eclogites has similar Mg no., but chlorite in "amphibolitites", particularly SN. 367, composed of coarse actinolite and interstitial chlorite (see section 8.3.4), are more Mg rich, with Mg no. greater than 0.75. **Epidote** occurs within the eclogites and garnet amphibolites. Epidote group minerals have the general formula $X_2Y_3Z_3(O,OH,F)_{13}$, where X is usually Ca, Y is usually Al and Fe''' and Z is Si. Zoisite has no Fe''', epidote has 1 Fe''' per formula unit. Epidote from the Western Lewisian rocks is of variable composition, from about 0.4 ions of Fe''', to a maximum of 0.9. In some rocks, particularly SN. 402, there are later overgrowths on earlier crystals. In all cases, the overgrowths are more Fe''' rich than the cores. **Sphene** in almost all samples is Al poor, the most aluminous being $CaTi_{0.95}Al_{0.05}Si(O,OH)_5$. In the

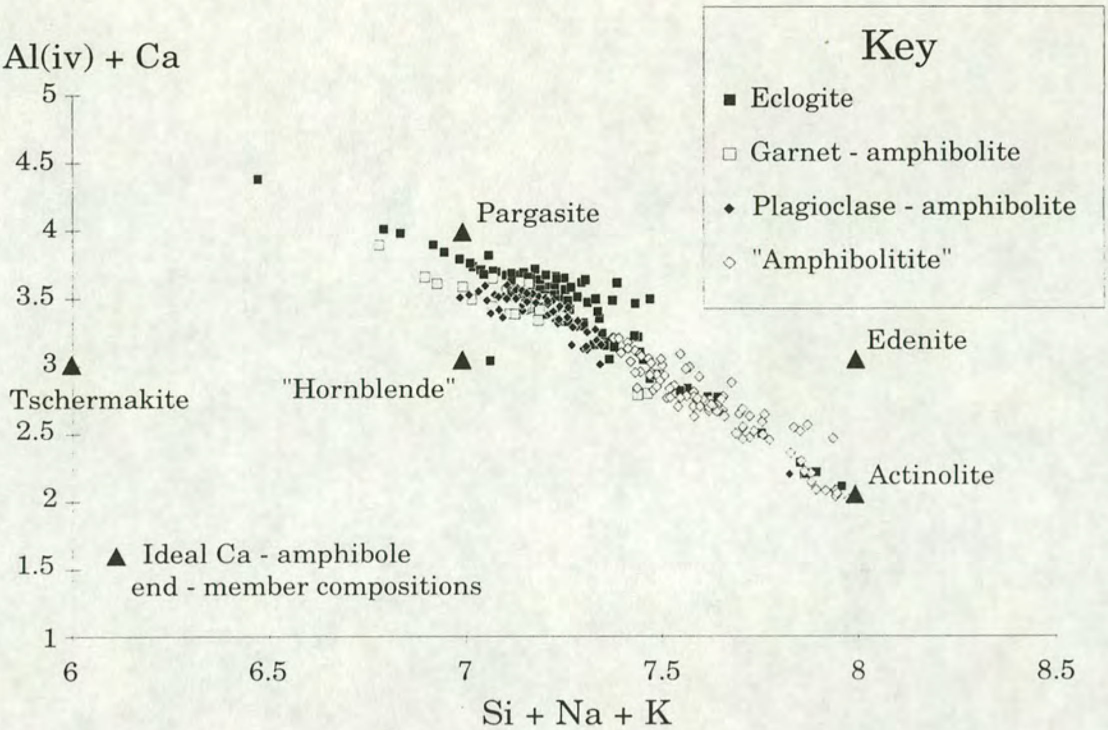


Figure 9.9 Plot for amphiboles of each of the main rock types of the Western Lewisian. (see chapter 8). Eclogite amphiboles are the most Al_{iv} rich, those from garnet and plagioclase amphibolites have comparable Si, Na, K contents, but lower Al_{iv}, Ca content. Amphiboles from the "amphibolitite" are generally Si rich, as are rare amphiboles from veins across the eclogite.

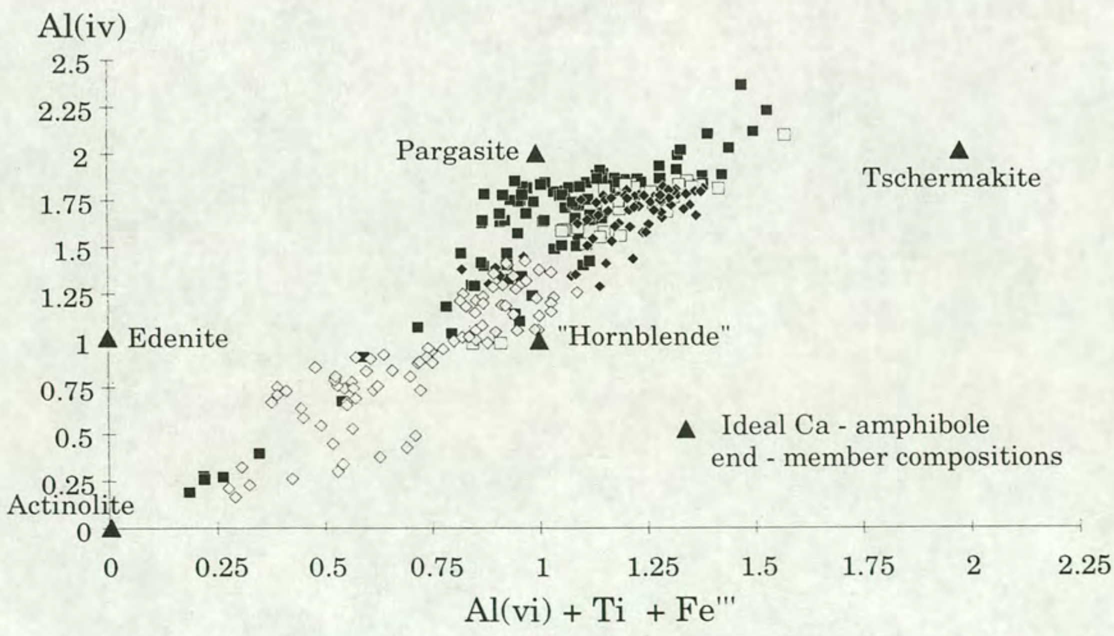


Figure 9.10 Western Lewisian amphiboles. (Symbols as in figure 9.9). Amphiboles in the eclogite are Al_{vi} poor compared to those from the garnet and plagioclase amphibolites. The "amphibolitites" are Al poor, ranging from hornblende to actinolite.

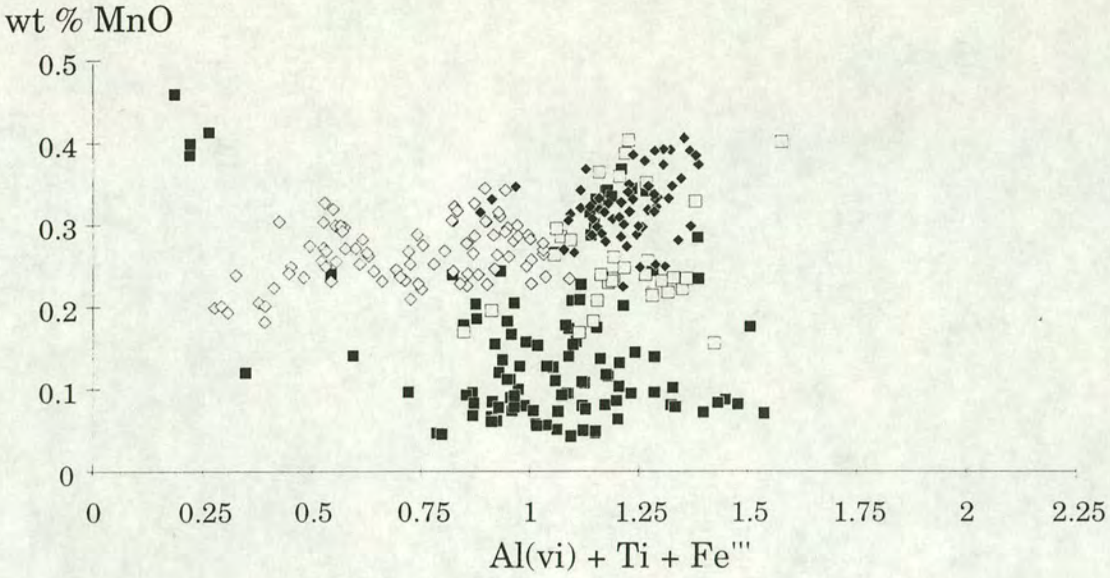


Figure 9.11 Amphiboles from the Western Lewisian. (symbols as in figure 9.9). Amphiboles from Western Lewisian eclogites are, generally, MnO poor. Those from other rocks have broadly similar Mn contents.

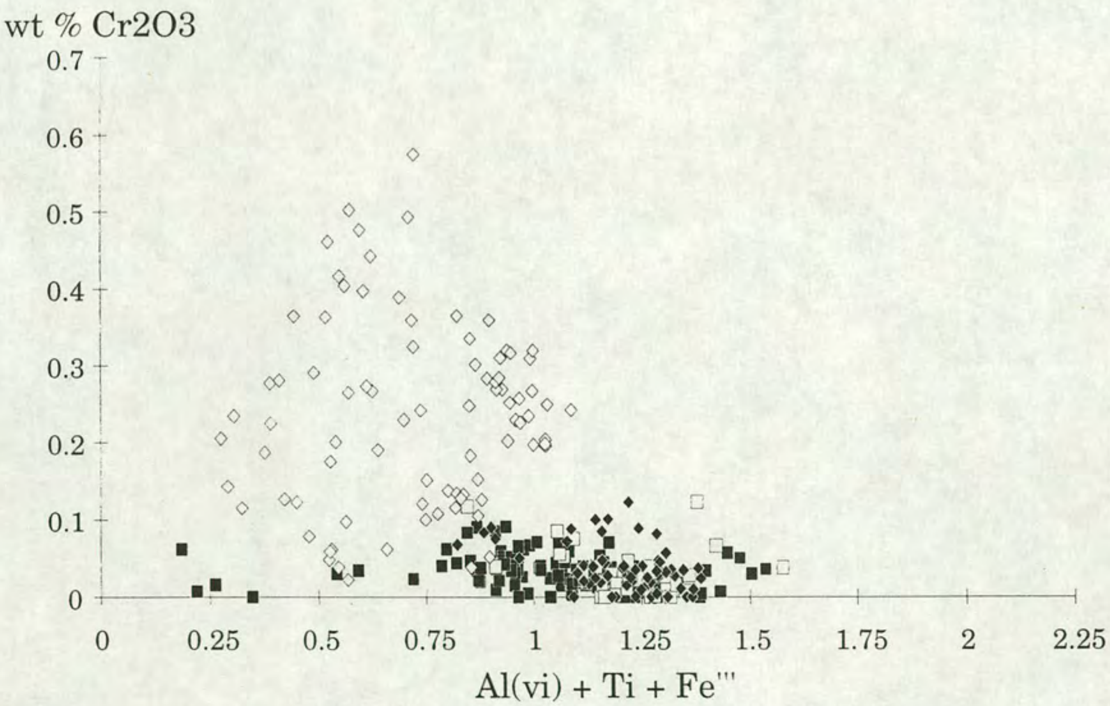


Figure 9.12 Western Lewisian amphiboles. (symbols as in figure 9.9). Amphiboles from the "amphibolitites" are generally Cr_2O_3 rich compared to those from other rocks, reflecting a difference in bulk composition.

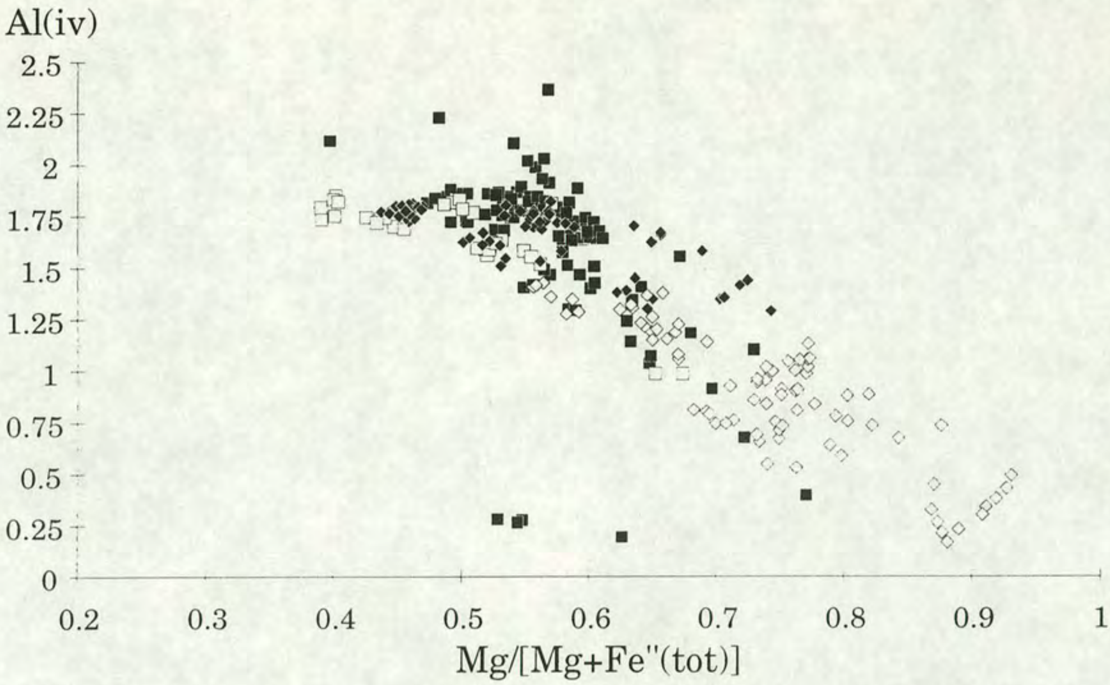


Figure 9.13 Western Lewisian amphiboles. (symbols as in figure 9.9). Amphiboles from the "amphibolitites" are Mg richest, those from garnet amphibolites Mg poorest.

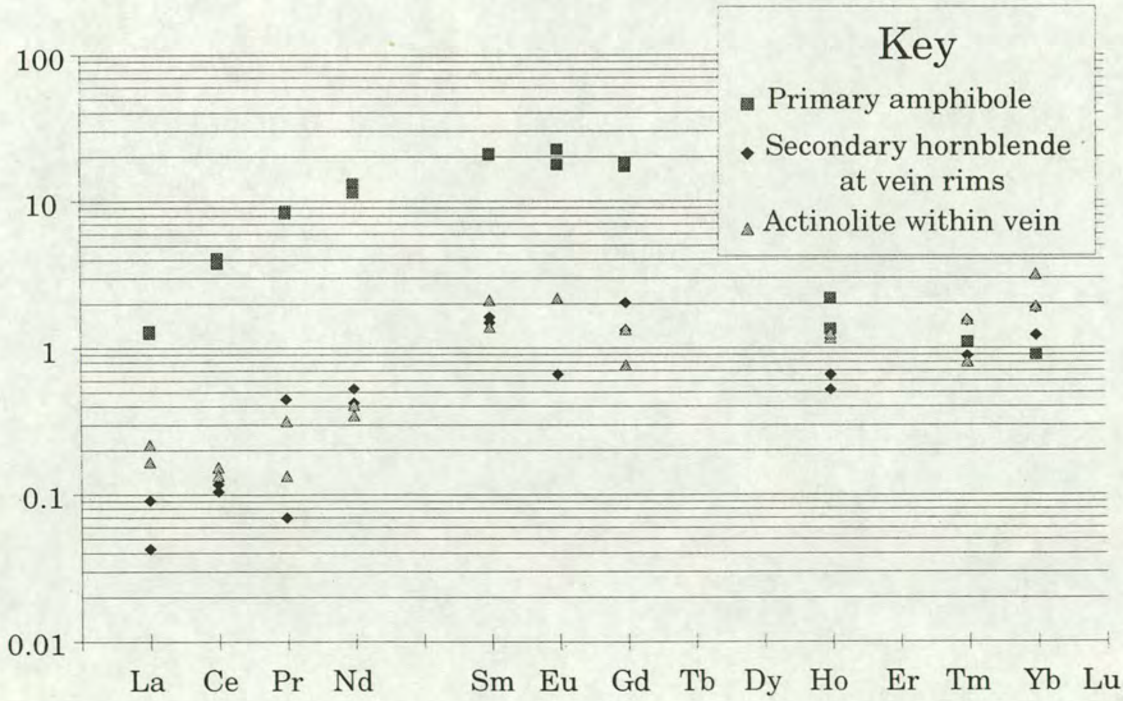


Figure 9.14 C1 chondrite normalised plot for REE's from amphiboles within a Western Lewisian eclogite (SN. 356). Primary amphibole has high middle REE concentrations. Both secondary hornblende alongside an actinolite - epidote vein and the actinolite from within the vein have low REE concentrations. A Eu anomaly for the hornblende suggests equilibration with plagioclase.

eclogites rare slightly pink, pleochroic crystals are relatively Al rich, as are rare crystals in one of the garnet amphibolites (SN. 108). The least titaniferous have approximate composition $CaTi_{0.87}Al_{0.09}Fe'''_{0.04}Si(O,OH)_5$.

9.3.5 Summary

Garnets within the Western Lewisian eclogites plot within the eclogite stability field of Mottana (1986), and have similar Ca to (Fe + Mg) ratios as the Eastern Lewisian bimineralic eclogites, but with lower Mg no. This is probably because the rocks have a bulk Mg no. lower than that of the Eastern Lewisian eclogites, and is probably not due to Fe - Mg exchange and equilibration at lower temperatures, because both garnet and clinopyroxene have a higher iron content than the Eastern Lewisian eclogites. Amphiboles from all the rock types apart from the "amphibolitites" are of similar composition. Eclogite amphiboles are similar in composition to those from quartz - eclogites in the Eastern Lewisian, but there are no Na - rich amphiboles characteristic of those seen in the bimineralic eclogite from the Eastern Lewisian. This may well be due to lack of exposure.

9.3.6 Thermobarometry

Pressures and temperatures of metamorphism, discussed in chapter ten, show the eclogites to have been metamorphosed at about 740 - 790°C, and at least 15 Kb. Retrogressed eclogite, amphibolites and Moine rocks all give conditions of metamorphism of about 650°C, 10 Kb.

9.5 Conclusions

The rocks of the Western Lewisian can be divided up chemically into two groups, the "amphibolitites", and all the other rocks, including the eclogites. Although these two groups of rocks could be related the "amphibolitites" also have a different textural history to the eclogites and other rocks (chapter eight) and from petrologic and field evidence (chapter seven) appear genuinely to be a completely different set of rocks. In chapter seven (after discussion of similar rocks within the Eastern Lewisian in chapter six) it was suggested that these rocks might well represent basic dykes intruded into the Lewisian after initial high grade metamorphism. It is interesting to note that the "amphibolitites" bear some resemblance chemically to the Eastern Lewisian bimineralic eclogite, but the "amphibolitites" show no sign of ever having been eclogites and the Eastern Lewisian eclogites certainly show no sign of becoming "amphibolitites".

In chapter five it was suggested that some of the quartz - (feldspar) rich eclogites may have formed due to the widespread intrusion of quartzo - feldspathic material into the rocks. Although the Western Lewisian eclogites have different chemistry to the Eastern Lewisian eclogite, being more silica rich, they may have belonged to a similar suite of rocks prior to the intrusion of such material (the QFK streaks in the Eastern Lewisian), and that a greater portion was intruded into the Western Lewisian rocks than the Eastern Lewisian.

PART FOUR
Thermobarometry

Chapter Ten

Thermobarometry

CHAPTER 10

THERMOBAROMETRY

10.1 Introduction

In chapters three to six and seven to nine it was suggested that both the Eastern and Western Lewisian rocks respectively had undergone at least two periods of metamorphism, at eclogite facies in the first instance, prior to Moine deposition or interleaving of Moine and Lewisian rocks, and later at amphibolite facies along with the Moine rocks.

A variety of thermometers and barometers have been used to determine the conditions of these metamorphic events, these being principally :

Thermometers :

1)	Grt - Cpx (Fe - Mg exchange)	: Krogh (1988) after Ellis and Green (1979)
2)	Grt - Bt (Fe - Mg exchange)	: Indares and Martignole (1985)
3)	Grt - Amph	: Graham and Powell (1984)
4)	Plag - Amph	: Blundy and Holland (1990)

Barometers :

5)	Jd + Qtz $\Leftrightarrow$ Alb	: Holland (1980, 1983)
6)	Grt + Ky + Qtz $\Leftrightarrow$ An	: Koziol and Newton (1988)
7)	Spn + Ky $\Leftrightarrow$ Rt + An	: Manning and Bohlen (1991)
8)	Grt + Musc $\Leftrightarrow$ Bt + An	: Hodges and Spear (1982)
9)	Pl + $Amph_1$ $\Leftrightarrow$ Grt + $Amph_2$ + Qtz	: Kohn and Spear (1990)

The various mixing models for these thermobarometers, and the activities used for calculation of K_D are given in appendix V. Representative analyses and calculated K_D's are also given in appendix V, along with a summary of all pressure / temperature data used. The differing effects of calculated Fe''' content of minerals used in thermometers is considered in appendix VI.

Calculation of pressures and temperatures for the formation of the Eastern Lewisian eclogites are restricted to eqns. 1) and 5). However, with biotite - eclogite and eclogite with apparently primary amphibole, biotite and plagioclase, eqns. 2), 3) and 4) may be used. QFK streaks within eclogites allow the use of eqns. 3), 6), 7) and 8). Eqns. 2), 6) and 8) are also used for the metasediments of the Eastern Lewisian and for Moine rocks. Conditions for the formation of symplectites can be estimated from eqn. 5), and conditions of alteration to produce amphibole - plagioclase rocks, eqn. 4). for the Western Lewisian eclogites, eqns. 1) and 5) are used, along with 2) and 3) where applicable. For the Western Lewisian amphibolites and garnet amphibolites, eqns. 3) and 4) are used, but there are no useful appropriate barometers.

Essene (1989) gave an overview of thermobarometry and discussed many of the pitfalls associated with the use of the above methods. These principally rest upon calculation of Fe''' content, the degree of non - ideal mixing between cation sites within minerals and the effects of minor cations upon the crystal lattice. It is only changes in the former that directly affect the calculated pressures and temperatures, most obviously in clinopyroxenes, where Fe content is generally low and changes in the proportions of Fe'' and Fe''' have a far greater affect than for other minerals. Droop (1987) and Ryburn *et al.* (1976) both suggested methods for calculating Fe''' in minerals. Theoretically the calculation will be reasonably accurate for minerals where it is reasonable to assume that there are no site vacancies, such as garnet and clinopyroxene, and for garnet and clinopyroxene both methods of calculation give similar estimates of Fe''' content. For biotite and amphibole, Essene (1989) suggests that mineral analyses be totalled excluding cations in sites where vacancies might be expected to occur, thus excluding K, Na and Ca in amphiboles and totalling to 13 for 23 oxygens, and excluding K, Na and Ca in biotite and totalling to 14 for 24 oxygens. Estimations of Fe''' for biotite and amphibole using the method of Droop (*op cit.*) are more open to doubt than for garnet or clinopyroxene, and Fe''' has been calculated after Ryburn *et al.* (1976). In appendix VI the effects of changing Fe''' and hence Fe'' content on Fe - Mg exchange thermometers is discussed. The garnet - clinopyroxene thermometer is particularly susceptible to change due to the low overall Fe content of clinopyroxene in the eclogites.

10.2 Results of previous work

Previously published data for the conditions of metamorphism of the Lewisian rocks are almost exclusively from the work of Sanders (1978, 1988, 1989), with one estimate from Manning and Bohlen (1992). Sanders (1978) suggested that the eclogites were metamorphosed at 650°C,>13.5 Kb and that the marbles were metamorphosed at 800°C, followed by recrystallisation at 650°C at the same time as eclogite facies metamorphism, the latter estimate obtained using calcite - dolomite thermometry. Sanders (1988) suggested that the QFK streaks showed evidence of being metamorphosed at 750°C, 17 Kb, from Grt - Cpx thermometry using the thermometer of Råheim and Green (1974) and the jadeite content of the pyroxene, and from An - Grs - Ky - Qtz equilibria, and showed that this metamorphism was prograde, probably occurring after initial eclogite facies metamorphism. Sanders (1989) suggested that both the eclogites and the marbles were metamorphosed at about 730°C, 16.5 Kb, confirmed by Manning and Bohlen (1992) in their calibration of an An - Rt - Spn - Ky barometer. Sanders (1989) also demonstrated that jadeite content of clinopyroxene in equilibrium with both plagioclase and quartz was between 40 and 50%, giving pressures of up to 17 Kb at 750° C. Sanders then described isothermal decompression for the eclogites with the re - growth of plagioclase down pressure through the breakdown of garnet and kyanite.

These latter pressures and temperatures of formation agree roughly with the results discussed below. However Sanders used constant Fe'''/Fe'' ratios for his garnet and clinopyroxene analyses, many of which are different to those calculated by stoichiometry. Recalculating Fe''' contents gives different temperatures of formation to those published by Sanders (1988, 1989). Sanders also calculates jadeite content to be equal to Na content, regardless of whether there is enough Al_{vi} within the pyroxene to make up the jadeite, which gives potentially spurious minimum pressures of formation. Sanders (1988) ignores some temperatures calculated by Fe - Mg exchange between garnet and clinopyroxene because the temperatures obtained cover a wide range, rather than suggesting that the wide range may occur due to partial retrogression or due to partial resetting of thermometers during syn - Moine metamorphism. Some of the data published by Sanders (1988, 1989) is re - calculated with Fe''' contents calculated by stoichimetric means in appendix VI. Re - calculated analyses show higher temperature conditions than those summarised by Sanders, generally up to 30°C higher, i.e. up to 760 °C or more, rather than 730°C. If calculated Fe''' contents are incorrect, this will also alter estimates for the jadeite content of the clinopyroxenes for reasons discussed in chapter five. Estimates of pressure and temperature re - calculated after Sanders (1988) are of 748°C,>14 Kb for initial eclogite facies metamorphism, and 793°C,>16 Kb for metamorphism along with QFK streaks.

Estimates for conditions of metamorphism of the surrounding Moine rocks have not been found in the literature, although, as mentioned in chapter two, Moine rocks close to Glenelg were estimated to have been metamorphosed at about 750°C, 8 Kb (Tanner, 1976) or 650 - 700°C, 6 - 8 Kb (Strachan and Treloar, 1985).

10.3. Results

10.3.1 Introduction

Data from representative garnet - clinopyroxene, garnet - biotite and amphibole - plagioclase pairs used in the appropriate thermometers are given in tables 10.1 - 3 respectively. These three thermometers provide the basis for understanding and interpreting the thermobarometric history of the rocks. Full details of these and other thermometers and barometers are given in the appendices. Figures 10.1 and 10.2 are summary P - T diagrams for the two main periods of metamorphism that have affected the rocks. Figure 10.1 is for high - pressure eclogite facies metamorphism in the Eastern Lewisian, figure 10.2 is for the later amphibolite facies metamorphism that affected all rocks in the area.

SN.	Rock type	K_D	X_{Ca-Grt}	X_{Jd-Cpx}	T (°C) at 16 Kb	P (Kb) at calc. T
E. Lew.						
E5	Bimineralic Eclogite	7.27	0.23	0.29	738	14.8
C4	Coarse Grt - Cpx	5.88	0.17	0.06	742	-
223	Orthopyroxene Ec.	5.44	0.11	0.27	715	14.2
83	Quartz Eclogite	10.08	0.34	0.28	740	14.7
E2	Bimineralic Eclogite, with primary amph.	6.85	0.27	0.35	783	16.3
96	Bimineralic Eclogite, with QFK streaks	6.70	0.27	0.44	789	17.2
224	Orthopyroxene Ec.	4.79	0.14	0.38	773	16.4
330	Quartz Eclogite	6.58	0.25	0.28	777	15.3
W. Lew.						
420 - A	Eclogite (core)	5.86	0.20	0.29	765	15.2
420 - B	Eclogite (rim)	6.50	0.27	0.24	798	14.8

Table 10.1 Summary data for Grt - Cpx pairs using the thermometer of Krogh (1988). Note that P (Kb) is a minimum pressure based upon the reaction Alb ⇔ Jd + Qtz.

SN.	Rock Type	K_D	X_{Ca-Grt}	T (°C)
E. Lew. Ec.				
512	Biotite Eclogite	0.23	0.11	777
E2	Bimineralic Eclogite with primary Biotite	0.30	0.27	763
E. Lew. Sed.				
8	Retrogressed Pelite	0.14	0.15	643
8	Pelite	0.21	0.15	755
86	Pelite	0.17	0.08	774
316	? Pelite	0.27	0.14	764
W. Lew. Ec.				
417	Eclogite	0.29	0.25	773
Moine				
100	Pelite	0.16	0.20	659
A1	Pelite	0.19	0.19	645

Table 10.2 Summary data for Grt - Bt pairs using the thermometer of Indares and Martignole (1985). Temperatures for the Moine are calculated at 10 Kb, all others are at 16 Kb.

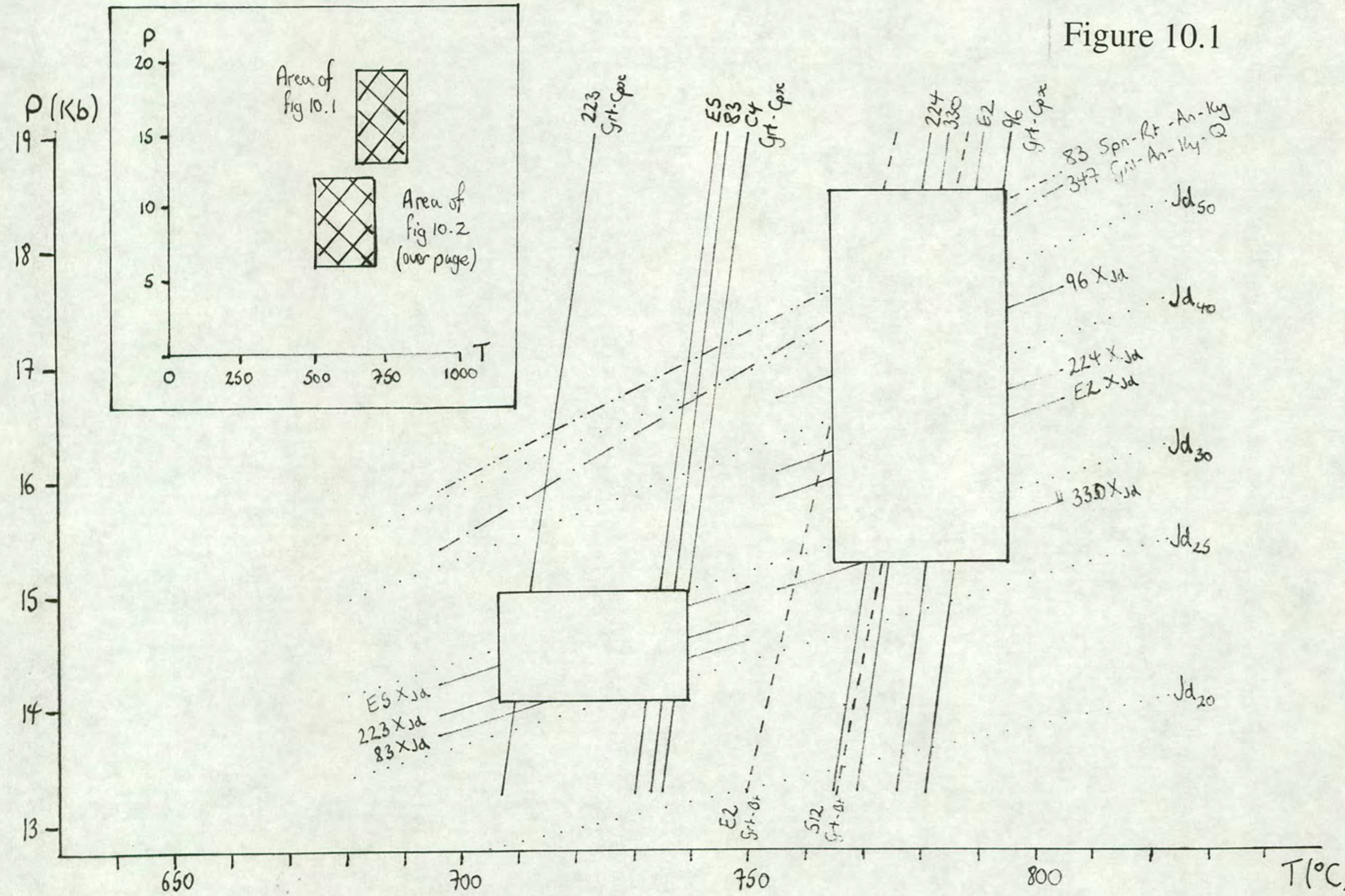
SN.	Rock Type	K_D	X_{An}	T (°C) at 10 Kb
E. Lew.				
E1	Eclogite - symplectite after clinopyroxene	1.67	0.19	622
264	Vein across Bimineralic Eclogite	1.56	0.17	632
347	Qtz. Ec. - symplectite after clinopyroxene	1.89	0.25	603
80	Amphibolite	1.53	0.20	636
W. Lew.				
420	Eclogite - symplectite after clinopyroxene	1.40	0.17	650
258	Amphibolite	1.64	0.17	625
372	Amphibolite	1.48	0.15	641

Table 10.3 Summary data for Amph - Plag pairs using the thermometer of Blundy and Holland (1990)

Over page : Figure 10.1 : Estimated P - T conditions for E. Lewisian eclogite facies metamorphism. W. Lewisian metamorphism occurred under similar conditions (table 10.1, appendix V). Jadeite isopleths after Holland (1980, 1983).

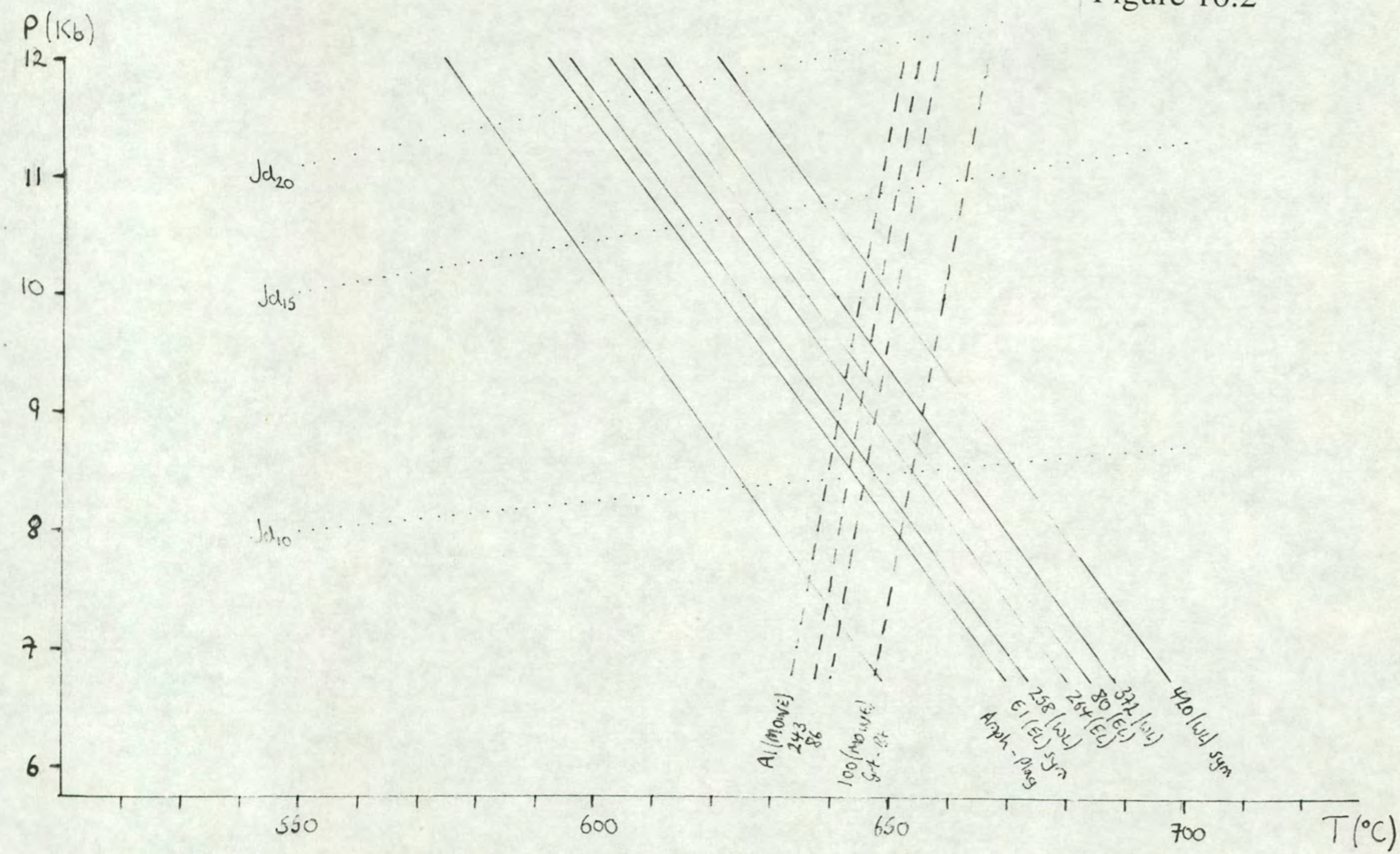
Second page : Figure 10.2 : Estimated P - T conditions for amphibolite facies metamorphism affected E. Lewisian, W. Lewisian and Moine rocks.

Figure 10.1



P (Kb)
19
18
17
16
15
14
13
T(°C)
650
700
750
800
P
20
15
10
5
T
0
250
500
750
1000
Area of fig 10.1
Area of fig 10.2 (over page)
223 Grt-Cpx
ES
83
C4
Grt-Cpx
224
330
E2
96
Grt-Cpx
83 Spn-Rt-An-Ky
347 Grt-An-Ky-Q
Jd50
96 X Jd
Jd40
224 X Jd
E2 X Jd
Jd30
330 X Jd
Jd25
Jd20
ES X Jd
223 X Jd
83 X Jd
E2 Grt-Or
512 Grt-Or

Figure 10.2


P (Kb)
12
11
10
9
8
7
6
Jd20
Jd15
Jd10
550
600
650
700
T (°C)
Al (MOWE)
243
86
100 (MOWE)
Gt - Bt
Amph - Plag
E1 (EL) sym
258 (WL)
264 (EL)
80 (EL)
372 (WL)
420 (WL) sym

10.3.2 Metamorphism in Eastern Lewisian eclogites

Estimates of the pressure and temperature of formation of the eclogites have been obtained using a variety of thermometers and barometers with varying degrees of accuracy. The only appropriate thermometer for most eclogites is the garnet - clinopyroxene Fe - Mg exchange thermometer. Many different variations have been proposed to take into account the effects of other ions within the garnet and clinopyroxene lattices, especially Ca in garnet. In this study the thermometer of Ellis and Green (1979) is used, with the corrections of Krogh (1988). There appear to be two main set of conditions, 710 - 750°C, 14 - 15 Kb, and 760 - 790°C, 16 - 17 Kb, although there is a wide spread of temperatures, down to ≈ 600°C, and up to over 840°C, the latter at pressures of approximately 16 Kb. Pressures are obtained from the jadeite content of clinopyroxene, which gives a minimum pressure estimate. The details of these are in appendix V, the results summarised in figure 10.1. All three main eclogite types have garnet - clinopyroxene pairs that give conditions in both the main groups above, although the pairs at the rims of QFK streaks, and from SN. E2, with primary amphibole and biotite, primarily occur in the latter group. The latter set of conditions are similar to those estimated for the metamorphism of QFK streaks by Sanders (1988).

For rocks where primary amphibole appears to be in equilibrium with garnet, principally the bimineralic eclogites from near to Lochan na Beinn Faide, the garnet - amphibole thermometer of Graham and Powell (1984) was used. Generally speaking, these pairs gave temperatures within the range 757 - 777°C, covering the range of temperatures suggested by the garnet - clinopyroxene thermometer. For those rocks where biotite and garnet appeared to be in equilibrium, including some of the bimineralic eclogites, and the biotite eclogite, the garnet - biotite thermometer of Indares and Martignole (1985) was used. This gave temperatures of between approximately 750 - 830 °C calculated at 16 Kb, the pressure estimated from the jadeite content of pyroxenes. Conditions of both garnet - amphibole and garnet - biotite thermometers are shown on figure 10.1.

The breakdown of Na - rich clinopyroxene is thought to have occurred on at least two separate occasions, with the occurrence of coarse and fine grained symplectite. The jadeite content of the pyroxene within the symplectite gives an indication of the pressure of formation. Co - existing plagioclase and amphibole after clinopyroxene within symplectites can also provide an estimate of the temperature of formation, using the thermometer of Blundy and Holland (1990). The coarse symplectite has a jadeite content of about 15 - 22 mole %, which yields minimum pressures of formation of about 11.5 - 13

Kb, at 700°C, assuming that the pyroxene is in equilibrium with both quartz and plagioclase. Fine grained symplectite has a jadeite content of about 9 - 17 mole %, yielding estimates of about 8 - 12 Kb at 700°C.

Co - existing amphibole and plagioclase as alteration products of all eclogite types give temperatures of about 573 - 697°C at 10 Kb, including those amphibole - plagioclase pairs occurring as symplectites after clinopyroxene. Garnet - amphibole pairs gave temperatures of 533 - 697°C, summarised in figure 10.2.

10.3.3 Metamorphism in QFK streaks within Eastern Lewisian eclogites and in quartzo - feldspathic rocks.

Pressure estimates within the QFK streaks may be obtained from coexisting garnet - anorthite - kyanite - quartz (Koziol and Newton, 1988) and from coexisting rutile - sphene - kyanite - anorthite (Manning and Bohlen, 1991). Fe - Mg exchange between garnet and biotite (Indares and Martignole, 1985) has been used for some rocks where biotite appears to be in equilibrium with the garnet. Estimates from co - existing garnet and clinopyroxene at streak rims has already been summarised along with data from the eclogites.

Garnet - biotite pairs for rare quartzo - feldspathic rocks that contain both minerals give estimates of about 755°C calculated at 16 Kb.

Pressure estimates for QFK streaks within the eclogites from are of 16 - 17.5 Kb at 750°C from sphene - rutile - anorthite - kyanite equilibria and 16 - 17 Kb from garnet - anorthite - kyanite - quartz equilibria.

The system kyanite - anorthite - margarite - zoisite - quartz within the QFK streaks and the quartz - eclogites provides excellent alternative estimates of pressure and temperature for the metamorphism of the rocks, particularly the later, syn - Moine metamorphism. Cotkin *et al.* (1988) summarised the details of the system. In section 4.3.4 the sequence of events leading to the formation and alteration of kyanite within the QFK streaks was thought to be :-

1) growth of kyanite.
2) (pre D_0) growth of plagioclase rims ($An_{\sim 80}$) on kyanite.
3) (post D_0) growth of margarite.

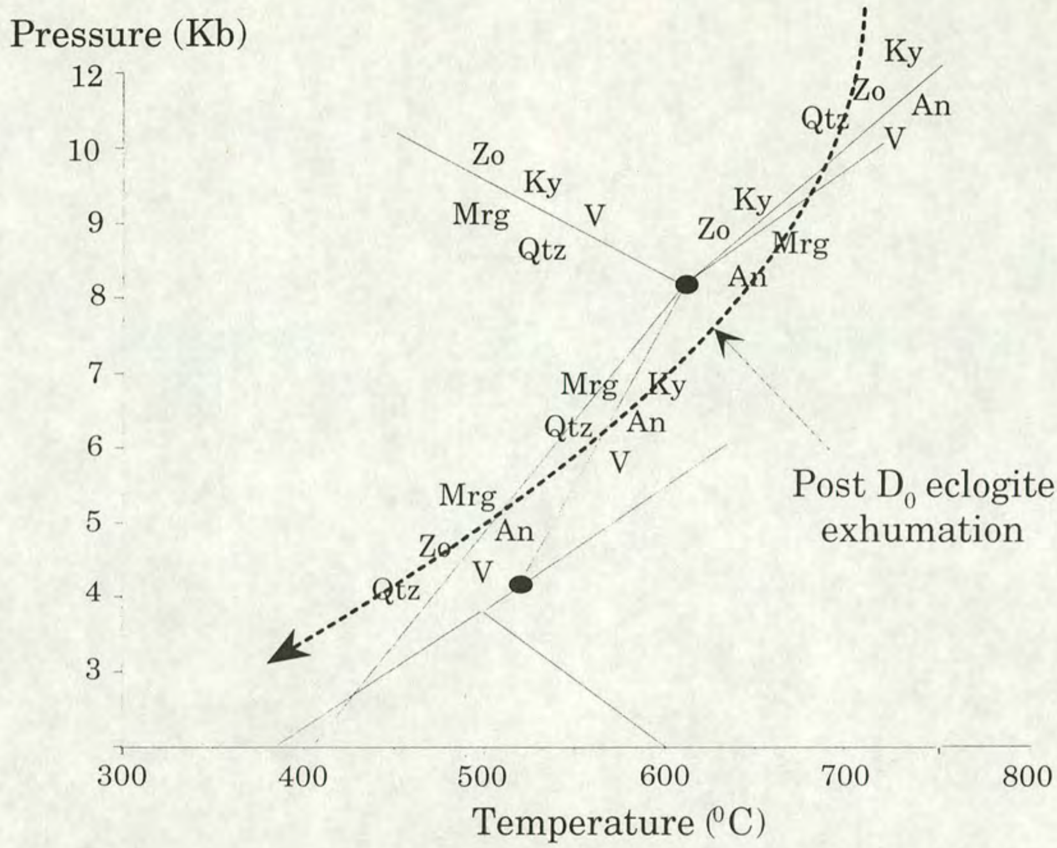


Figure 10.3 : P - T plot with Mrg - Ky - An - Zo equilibria, after Cotkin *et al.* (1988)

4) (syn D_2) alteration of margarite and/or remaining kyanite to Ms and Zo.

The invariant point for the reactions between the phases Ky, Qtz, Zo, Mrg, An and H_2O is at 8.2 Kb, 610°C (Cotkin *et al.*, *op cit.*), summarised in figure 10.3. Events 1) and 2) occur by the reactions Grs + Ky + Qtz $\Leftrightarrow$ An, and occur at high pressure and temperature. The estimates for event 2), using the barometer of Koziol and Newton (1988), are 17 Kb at 750°C. Event 3) probably occurs with Ky + An + H_2O $\Leftrightarrow$ Mrg + Qtz, down pressure and temperature from the invariant point of the system (figure 5.18), above the kyanite - sillimanite - andalusite invariant point. This implies that the rocks were retrogressed on a clockwise path.

The production of zoisite and muscovite from kyanite is difficult to interpret. The production of muscovite is probably a result of the reaction Kfs + Ky + H_2O $\Rightarrow$ Ms + Qtz, with hydration of Ksp + Ky at any point below the muscovite breakdown reaction. In the Ca - Al - Si - H_2O system, the growth of zoisite from margarite is always on the kyanite side of reactions, thus the growth of zoisite implies the growth of secondary kyanite too, which is highly unlikely.

The effect of changing plagioclase composition from pure anorthite is to increase the pressure of this reaction (Cotkin *et al.*, 1988). The initial production of margarite was suggested as being of post - D_0 age (chapter four), occurring with exhumation of the eclogites prior to Moine deposition. The growth of zoisite (and muscovite) was interpreted as being of D_2 age.

10.3.4 Metamorphism of Eastern Lewisian metapelites

Estimates for the conditions of metamorphism of the pelites are gained from garnet - biotite thermometry and theoretically from An - Grs - Ky - Qtz equilibria for the pressure, but the latter does not give realistic pressures (upwards of 40 Kb !!). Temperature estimates cover a wide range, of 648 - 755°C calculated at 10 Kb. Most of the samples from Lochan na Beinne Faide yielded unrealistically high temperatures of up to 1000°C.

Despite the lack of pressure data, the temperatures for the kyanite - bearing pelites are broadly compatible with those temperatures gained from garnet - clinopyroxene pairs in the eclogites. The kyanite - free rocks are thought to represent deformed versions of the kyanite bearing rocks (see chapter six) and thus the temperatures may represent re - equilibration during, or immediately after, deformation. One sample has probable co - existing garnet - biotite - muscovite - plagioclase, and use of the barometer of Hodges and Spear (1982) gives pressures of about 11.5 Kb at 650°C.

10.3.5 Metamorphism of nodules within Eastern Lewisian marbles

Some thermometry was attempted using the minerals within nodules in the marbles. Because of uncertainty as to which phases were co - existing, thermobarometry is of limited value, and only SN. 261 contains garnet, biotite and amphibole in apparent equilibrium. The garnet - amphibole thermometer of Graham and Powell (1984) gave temperatures at 10 Kb of about 516 - 539°C, the garnet - biotite thermometer of Indares and Martignole (1985) gave a temperature of 731°C calculated at 10 Kb and the garnet - clinopyroxene thermometer of Ellis and Green (1979) gave 502°C calculated at 11 Kb, with the pressure estimate from the jadeite content of the pyroxene, being a minimum value.

Other samples show higher temperatures, similar to those from the eclogites. SN. 260 gave estimates of 610° calculated at 13 Kb using the garnet - clinopyroxene thermometer, and of 740°C calculated at 12 Kb using the garnet - biotite thermometer. The garnet - anorthite - kyanite - quartz barometer gave pressures of 16 Kb at 750°C. The pyroxenites, SN.'s 312 & 313, with secondary garnet, gave garnet - clinopyroxene estimates 634 - 752°C, calculated at 10 Kb. SN. 263 gave an estimate of 765°C calculated at 14 Kb, for co - existing garnet - clinopyroxene, with the pressure estimate from the jadeite content of the pyroxene.

On the whole the samples with garnet and clinopyroxene range up to at least 750° C, similar to the temperatures obtained from the eclogites and from the pelites.

10.3.6 Metamorphism of Western Lewisian eclogites

Estimates for the metamorphic conditions of the Western Lewisian eclogite are derived primarily from garnet - clinopyroxene equilibria, but also from garnet - biotite and garnet - amphibole equilibria. Garnet - clinopyroxene equilibria gives temperatures of 740 - 800°C, at pressures of at least 15 Kb, estimated from the jadeite content of the pyroxene. Other thermometers give wider ranges of temperatures, garnet - biotite equilibria give 710 - 773°C calculated at 16 Kb, garnet - amphibole give temperatures of 716 - 747°C. Estimates of pressure from apparently coexisting garnet - amphibole - plagioclase gave ≈ 15 Kb at 700°C. These conditions are roughly similar to those obtained for the Eastern Lewisian eclogites, although the minimum pressure estimates from jadeite content of clinopyroxene are slightly lower.

The jadeite content of clinopyroxene within symplectites with plagioclase is generally about 9 - 10 mole %, giving pressure estimates of about 7.5 Kb at 700°C. The temperatures obtained from co - existing amphibole - plagioclase replacing clinopyroxene symplectites are about 650 - 670°C calculated at 10 Kb.

The results of thermobarometers for the Western Lewisian are summarised in appendix V.

10.3.7 Metamorphism of Western Lewisian granulites from north of Loch Duich

Analyses of fresh granulites from north of Loch Duich, discussed by Barber and May (1975) are not published. Two specimens collected for this thesis are both retrogressed (chapter eight). Temperatures and pressures calculated are not therefore those of granulites, but of their retrogressed equivalents. The samples give temperatures of 625 - 685°C from coexisting garnet - amphibole and 680°C Calculated at 13 Kb from coexisting plagioclase - amphibole.

10.3.8 Metamorphism of Western Lewisian amphibolites

The rocks of the Western Lewisian are mostly of restricted amphibolite facies mineralogy, although garnet - amphibole thermometry after Graham and Powell (1984) is used for the few garnet - bearing rocks. This thermometer gives temperatures of 611 - 625°C for three garnet - amphibolites. Coexisting amphibole - plagioclase from veins in the eclogites give temperatures of about 630 - 650°C Calculated at 10 Kb, using the thermometer of Blundy and Holland (1990). Estimates from Western Lewisian amphibolites using the same thermometer are 641 - 718°C for garnet - bearing and garnet - free amphibolites. Garnet - amphibole - plagioclase assemblages mostly give pressures of ≈ 12 Kb at 600°C using the barometer of Kohn and Spear (1990). These conditions are summarised in figure 10.2.

10.3.9 Metamorphism of Moine rocks

Garnet - biotite pairs from the Moine give temperatures of 645 - 659°C Calculated at 10 Kb, using the thermometer of Indares and Martignole (1985). These are broadly similar to those suggested by previous workers. Apparently co - existing garnet - plagioclase - biotite - muscovite do not give realistic pressures using the barometer of Kohn and Spear (1990).

10.4 Conclusions

There are two main sets of pressures and temperatures, one for the eclogites from both Eastern and Western Lewisian and one for amphibolites, retrogressed eclogite and the Moine.

Estimates for the conditions of metamorphism of both the Eastern and Western Lewisian eclogites are similar. The Eastern Lewisian eclogites show two sets of conditions, one at about 730°C, 15 Kb, one at about 780°C, 17 Kb, the latter representing quartz eclogites, QFK streaks and bimineralic eclogites with primary amphibole and/or biotite. The Western Lewisian rocks show only a range of conditions from 750 - 800°C and at least 15 Kb, although the rocks do show two sets of textures similar to those in the Eastern Lewisian, i.e. large anhedral crystals replaced by finer polygonal crystals apparently in equilibrium with amphibole, biotite and plagioclase. Some samples of Eastern Lewisian metapelite and nodules within the marble show similar temperatures of metamorphism. There is no real evidence for isothermal decompression after the peak of metamorphism, rather, for the Western Lewisian in particular, there is evidence for cores of crystals having higher pressure and lower temperature than rims, indication a normal clockwise path of metamorphism.

Most other rocks, including the Moine, and also some samples of the eclogite and veins across the eclogites from both Eastern and Western Lewisian all show a similar range of temperatures of metamorphism, of about 600 - 700°C. A few estimates of pressure suggest that this was at 8 - 10 Kb, or even higher. Symplectites after clinopyroxene in retrogressed eclogites seem to have formed at reasonably high pressures, at least 8 Kb at 650°C. The pressures indicated by the fine - grained symplectite in the Eastern Lewisian and by symplectites in the Western Lewisian are similar to those estimated for Moine metamorphism. Coarse symplectite in the Eastern Lewisian probably formed at higher pressures, and probably formed during initial uplift of the eclogites prior to Moine deposition.

PART FIVE
Conclusions

Chapter Eleven

Discussion and Conclusions

CHAPTER 11

Discussion and Conclusions

11.1 Introduction

At the end of each chapter in this thesis there were summaries and discussions of the information presented. These have been summarised in table 11.1 and figure 11.1. Chapters three and seven contained field descriptions of the Eastern and Western Lewisian rocks respectively. The basis of table 11.1 is derived from these chapters. Chapters four and eight contained petrographic descriptions of basic rocks from the Eastern Lewisian and of all rocks from the Western Lewisian, respectively, and developed and confirmed the history of the rocks outlined from field evidence. Eclogitic rocks had been deformed in both a brittle and ductile manner. In the former case, there was complete retrogression of the eclogite on a number of occasions, in the latter case cracks formed and were filled by a mineralogy identical to that forming in the ductile rocks, with eclogitic mineralogy preserved elsewhere in the rock. Chapters five and nine dealt with the chemistry of the Eastern Lewisian basic rocks and the Western Lewisian rocks, respectively. In chapter nine in particular, it was possible to distinguish chemically between two broad groups of rocks, one set of varied rocks that were metamorphosed to eclogite facies, and one set of basic and ultrabasic rocks that were probably not. Chapter six describes both the chemistry and petrology of all the non - eclogitic rocks of the Eastern Lewisian, with particular emphasis placed upon the occurrence of metabasic nodules within the marble and on basic and ultrabasic rocks that were apparently not metamorphosed at eclogite facies conditions. Chapter ten summarised and interpreted the thermobarometric data from both the Eastern and Western Lewisian. Figure 11.1 is derived from these chapters.

It is apparent that the Western and Eastern Lewisian rocks have broadly similar histories. Interpretation of the history of the rocks at Glenelg rests on the presence or absence of dykes within the Eastern Lewisian and on whether possible dykes in either the Eastern or Western Lewisian were metamorphosed to eclogite facies or not.

The most important points are as follows :

table 11.1 Summary of the history of the Glenelg Inlier.

P/T conditions are illustrated in figure 11.1.

Eastern Lewisian	est. **P/T**	**Def.**	**Western Lewisian**
Garnet - bearing rock, anhedral crystals	**A:** 15 Kb, 730°C		? garnet - bearing rock, anhedral crystals
Quartz - feldspar - (kyanite) veins (+/- garnet). Growth of polygonal garnet Growth of black amphibole, biotite, quartz and feldspar within eclogite	**B:** 17 Kb, 780°C		Growth of polygonal garnet ? growth of plagioclase - biotite intergrowths within eclogite
Deformation, recrystallisation		D_0	Deformation
Formation of symplectites after clinopyroxene	**C**		Formation of symplectites after clinopyroxene
Intrusion of basic dykes			Intrusion of basic and ultrabasic dykes
Moine deposition	**D:** surface		Moine deposition
Deformation → strong fabric in garnet - amphibolite and in quartzo - feldspathic strips. Interleaving of Moine and Lewisian		D_1	Deformation: shearing, produces strong foliation & isoclinal folds. Interleaving of Moine and Lewisian
EITHER Deformation → strong fabric with lineation, or folding. OR Cracking → hbl - plag veins Also sliding & mylonitisation		D_2	Deformation: further shearing or crenulation and minor tight folding, produces lineation & axial planar cleavage. NE plunge to folds.
Growth of randomly oriented amphibole	**E:** ≈ 8.5Kb, ≈ 650°C		Growth of randomly oriented amphibole, biotite and rare garnet.
EITHER Deformation → open folds, tight minor folds OR Cracking → ep - act veins	**F**	D_3	Deformation : open folds. SE plunge
Cracks & microfaults		D_4	Cracks & microfaults

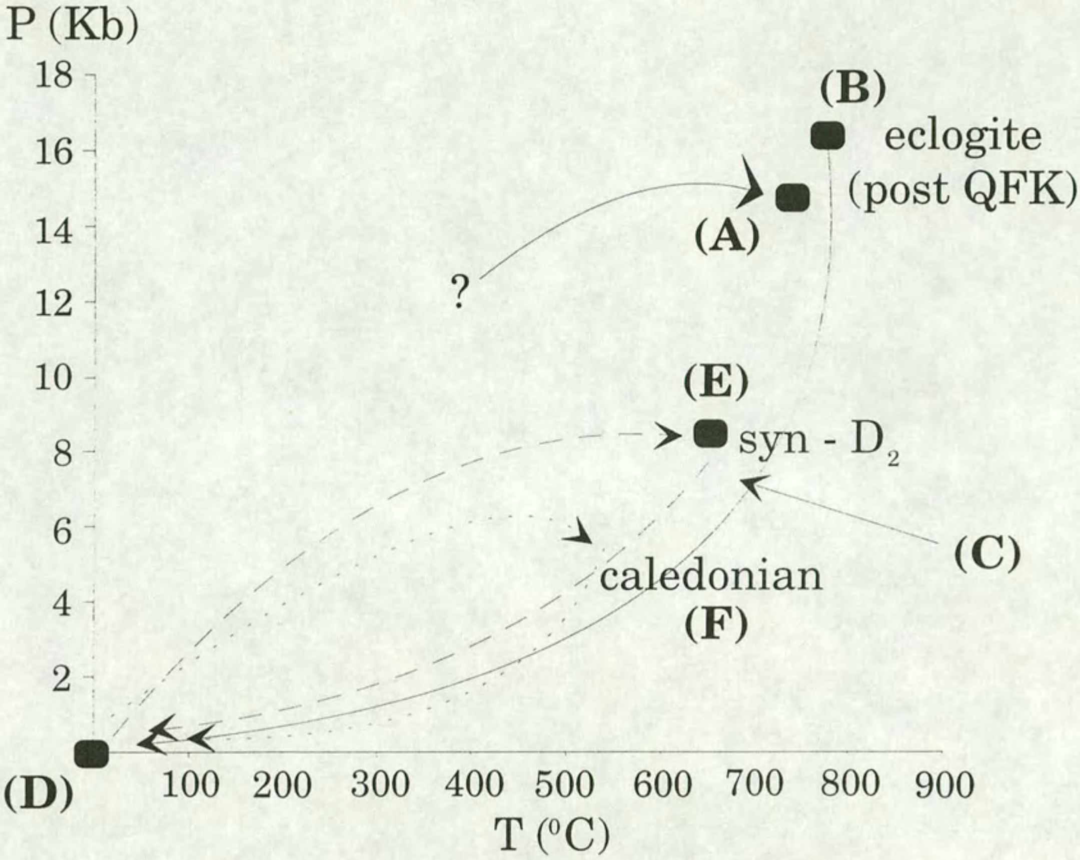


Figure 11.1 P - T diagram for the Glenelg rocks, based upon estimates for the Eastern Lewisian rocks discussed in chapter ten. Events (A) - (F) are marked on Table 11.1. Western Lewisian P - T are similar to those of the Eastern Lewisian, although two seperate high pressure events are not distinguished. The timing of these events is possibly B: ≈ 2500 Ma, C: prior to ≈ 2200 Ma, E: ≈ 1000 Ma? and F: ≈ 450 Ma.

The **Western Lewisian** eclogites were metamorphosed at 740 - 790°C and at least 15 Kb (chapter ten). There is textural evidence that all the Western Lewisian rocks but for the "amphibolitites" were also metamorphosed to eclogite facies (chapter eight). These rocks were affected by an early deformation, possibly at eclogite facies, and pre - date the intrusion of basic and ultrabasic dykes, the "amphibolitites", that were probably never metamorphosed to eclogite facies (chapters seven and eight). The whole sequence was later deformed and metamorphosed along with the surrounding Moine rocks at > 600 °C, > 8 Kb. The Western Lewisian rocks from south of Loch Duich are similar to those occurring north of Loch Duich (Barber and May, 1975) and also similar to the Lewisian of the foreland (Watson, 1975), except that they have suffered eclogite facies metamorphism rather than granulite facies metamorphism.

The **Eastern Lewisian** eclogites were metamorphosed at ≈ 730°C, 15 Kb, then again at ≈ 780°C, 17 Kb (chapter ten), the latter occurring after the probable intrusion of quartzo - feldspathic melt (chapter five). There is evidence that most of the rocks within the Eastern Lewisian, including amphibolites and metasediments, were also originally metamorphosed to eclogite facies, although some basic and ultrabasic rocks were probably not (chapter six). All the rocks of the Eastern Lewisian were deformed and metamorphosed along with the surrounding Moine rocks at > 600°C, > 8 Kb.

Correlation of the early, pre - Moine histories of the Western and Eastern Lewisian rests upon the recognition of basic dykes cutting across both groups of rocks, which in neither case have been metamorphosed to eclogite facies. For the Western Lewisian it is not proven, but only likely, that cross - cutting dykes were not metamorphosed to eclogite facies (chapters seven - nine), whilst in the Eastern Lewisian there is very little evidence at Glenelg even for the presence of cross - cutting dykes. However, it is felt that there is enough evidence to suggest that there may have been dykes, and the consequences of this premise are discussed. If both the Western and Eastern Lewisian are cut by dykes, then their textural histories can be correlated and they would appear to have undergone a similar history, both after the Moine deposition (as suggested by all previous authors, e.g. Ramsay, 1958) **and** prior to the Moine deposition.

11.2 The age of the Glenelg eclogite

Sutton and Watson (1958) tacitly assumed that both the Eastern and Western Lewisian had undergone similar histories and were of Scourian age, because of the sequence of high grade metamorphism followed by the intrusion of basic dykes, seen in the Western Lewisian at Glenelg, and in some other Lewisian inliers in the Moine, in particular the Scardroy inlier (Sutton and Watson, 1962). The evidence presented in this thesis and in all the previous work on the Lewisian rocks of Glenelg (in particular Ramsay, 1958; Sutton and Watson, 1958) has led to a conflict between field and petrological evidence and isotopic evidence over the age of the rocks, particularly with respect to the age of eclogite facies metamorphism. Field and petrological evidence suggests that the rocks have a similar history to those of the foreland Lewisian, affected by a period of high grade metamorphism prior to the intrusion of basic dykes (chapters five, seven & eight), suggesting that the eclogite is of Scourian age (≈ 2700 - 2500 Ma) **if** the dykes are Scourie dykes. However, isotopic data leads to the conclusion that the eclogites are of Grenville age (≈ 1000 Ma, Sanders *et al.*, 1984). It is pertinent therefore to summarise the history of the Grenville province of Canada which probably lay close to Glenelg at ≈ 1000 Ma, and to compare that history with that of Glenelg to see if any correlations can be drawn.

11.2.1 Summary of the history of the Grenville province of Canada

The Grenville province covers a large area of Quebec and Ontario and conditions of metamorphism vary widely over the area. General Grenville history is summarised by Mezger *et al.* (1993), Jamieson *et al.* (1992) and Indares and Martignole (1990). Archaean rocks (≈ 2850 - 2450 Ma, Duig, 1977) were intruded by granitic rocks at ≈ 1684 - 1600 Ma and then metamorphosed to granulite facies, at about 8 - 9 Kb, 700 - 800°C, prior to the intrusion of a suite of basic dykes at 1450 - 1235 Ma. These rocks formed the basement to a thick series of metasediments, the Grenville supergroup, comprising quartzites, pelites and marbles, which were deposited prior to metamorphism of basement and cover at 1200 - 1000 Ma. This metamorphism occurred at different times in different parts of the province and at differing pressures and temperatures, and resulted in the interleaving of slices of basement and cover and their subsequent metamorphism and deformation. In parts this metamorphism was to granulite facies, at about 800°C, 10 - 11 Kb (Anovitz and Essene, 1990), whilst Indares (1993) records relicts of eclogite facies mineralogies, but most rocks were metamorphosed under amphibolite facies conditions of about 600 - 800° C, 6 - 9 Kb. Trzienski (1988) records eclogite relicts from Greenland, but concludes that they are most likely of Caledonian age. It is interesting to note that Tuccillo *et al.* (1990) recorded isothermal decompression in these rocks, from 11.8 Kb to 6.8 Kb at 750°C, perhaps similar to isothermal decompression of the Glenelg rocks from about 17 Kb to less than 10 Kb at about 750°C (Sanders, 1988, this thesis).

11.2.2 Glenelg correlations

The options presented in chapter two for the history of the Glenelg rocks are repeated below and the arguments for and against are discussed. In each case it is assumed that the Western Lewisian rocks can be correlated with the Scourian of the foreland, because there is a demonstrable unconformity between the Western Lewisian and the Moine (e.g. Peach *et al.*, 1910) and because there are cross - cutting dykes that appear not to have been metamorphosed at high pressure.

A: The Western Lewisian granulites are Scourian, the Eastern Lewisian eclogites are Grenville, metamorphosed at ≈ 1000 Ma prior to the deposition and subsequent deformation and metamorphism of the Moine and re - working of the Lewisian at ≈ 750 Ma (as suggested by Sanders *et al.*, 1984).

The main reason for suggesting a correlation between the Glenelg rocks and the Grenville province is an isotopic age of ≈ 1050 Ma (Sm - Nd in garnet - clinopyroxene - whole rock) for the Glenelg eclogites (Sanders *et al.*, 1984), coupled with the discovery of eclogite relicts within the Grenville (Indares, 1993). The ≈ 1000 Ma age for D_2 metamorphism of the Moine suggested by Brook *et al.* (1976, 1977) is widely thought to be incorrect, and Rogers (pers. comm.) suggests that pegmatites in the Moine that post - date a deformation are ≈ 800 Ma, the oldest age seen in Moine rocks. However, it was demonstrated in chapter ten that the rocks of the Eastern Lewisian were re - metamorphosed at over 600°C and Mezger *et al.* (1992) suggested that the Sm - Nd isotopic systematics of garnets would only be preserved at over ≈ 600°C if the garnets were 30 cm across, and that any garnets less than 5 cm across would show no Sm - Nd evidence at all for the early metamorphism of polymetamorphosed rocks. Also the Grenville metamorphism represents interleaving of cover, a series of pelites and psammites, and basement, previously metamorphosed gneisses. Sanders *et al.* (1984) and Sanders (1989) suggest that the eclogites were formed by metamorphism due to Grenville compression, and that the interleaving of cover and basement, i.e. Moine and Lewisian, occurred at later date during some unique Scottish "Morar" event. It seems more reasonable that if the Grenville is represented in Scotland then it would also occur as an interleaving of cover and basement. Both these latter reasons cast doubt over the interpretation that the eclogites are of Grenville age, metamorphosed to eclogite facies prior to Moine deposition after the Grenville. The Sm - Nd age of ≈ 1050 Ma would thus be interpreted as the age of re - metamorphism of the eclogite and allied metamorphism and deformation of the Moine. The suggestion of the presence of dykes not metamorphosed at eclogite facies in this thesis, and in Barber (1968), May *et al.* (1993) and for other Lewisian inliers in the Moine, also casts some doubt on the interpretation that eclogite facies metamorphism occurred after dyke intrusion.

B: The Western and Eastern Lewisian high grade rocks are both Scourian and both groups of rocks have suffered a similar history, with deformation and metamorphism of the Moine and re - working of the Lewisian at ≈ 1000 Ma.

C: The Western Lewisian granulites are Scourian, the Eastern Lewisian eclogites represent Grenville basement (> 1450 Ma), the Moine was deformed and metamorphosed and the Lewisian re - worked at ≈ 1000 Ma.

Points B and C are similar. Both require that there were dykes in the Eastern Lewisian, which has not been conclusively proved, only inferred, and that dykes in the Western Lewisian and odd rocks that may have been dykes in the Eastern Lewisian were not metamorphosed to eclogite facies, also not conclusively proved, and that Sm - Nd dating on the eclogites represents resetting due to later metamorphism along with the Moine rocks, also not proved. However, other inliers of Lewisian rocks further east within the Moine do contain cross - cutting basic dykes (e.g. Watson, 1975), and the presence of marble bands suggests that these other inliers are similar to the Eastern Lewisian rather than the Western Lewisian. There are, therefore, arguments for suggesting that the Eastern and Western Lewisian eclogites may well at least be older than Grenville metamorphism. The history of both the Scourian and the Grenville province are similar (albeit with different ages) with the intrusion of granitic material into already metamorphosed rocks prior to high grade metamorphism, followed by the intrusion of basic dykes, the deposition of sediments and then further metamorphism and deformation, mostly at amphibolite facies. If it is accepted that dykes cutting across the Glenelg rocks have not been metamorphosed to eclogite facies, this sequence of events would place the Glenelg eclogites alongside either the granulite facies rocks of ≈ 1600 - 1450 Ma in the Grenville province, because these occur prior to the basic dyke intrusion, or else alongside ≈ 2500 Ma Scourian granulites. With no isotopic evidence to back the argument there is little difference between B and C, although U - Pb dating on other

Lewisian inliers within the Moine (e.g. Moorbath and Taylor, 1974) suggests that they are more likely to be of Scourian age.

D: The Moine was not deposited onto the exposed Eastern Lewisian, rather Grenville age metamorphism at ≈ 1000 Ma affected both the Eastern Lewisian and the Moine synchronously, with the Lewisian buried deeper than the Moine. The two groups of rocks were subsequently bought together during deformation at ≈ 1000 Ma in D_1.

The age of the Moine and of the initial deformation and metamorphism of the Moine are open to conjecture and do allow for the possibility for the metamorphism of the Moine at ≈ 1000 Ma, suggested by the dates of Brook *et al.* (1976, 1977). It is possible to satisfy the published age dates and the criteria of Grenville style metamorphism, with cover and basement interleaving and metamorphism, if both the Moine and the Eastern Lewisian were metamorphosed at ≈ 1000 Ma. As such, this is a satisfactory option, given that there is also no real evidence for uplift tectonics in the Eastern Lewisian prior to D_1. However, there is evidence for some deformation affecting eclogite facies rocks prior to Moine deposition (D_0), and whilst there is no concrete evidence that the Moine was deposited onto the Eastern Lewisian, it is assumed that it was from the sedimentary succession within the Moine (e.g. May *et al.*, 1993). Everywhere in the Moine above both the Western and Eastern Lewisian, a basal pelite occurs beneath a sequence of thicker semi - pelites and that there is no evidence for thrusting or sliding along Eastern Lewisian - Moine boundaries, except for the central Moine strip.

11.2.3 Summary

None of the above options for the history of the rocks has been conclusively proved or disproved. However the following points, discussed in the thesis, suggest that options A and D are the least likely :

- Ages of 1000 Ma for the eclogites might well represent the age of re - metamorphism along with the Moine and not eclogite facies metamorphism prior to Moine deposition.
- There are the possible presence of basic dykes within both the Eastern and Western Lewisian that have probably not been metamorphosed to eclogite facies.

- The Moine was almost certainly deposited onto both the Eastern and Western Lewisian, therefore metamorphism could not have occurred synchronously.

Options B or C therefore seem the most likely interpretation for the history of the rocks. Scourian dates from other inliers further east within the Moine suggest that the Eastern and Western Lewisian were probably both metamorphosed to eclogite facies during the Scourian.

11.3 Relationships between the Eastern and Western Lewisian

If the Glenelg Lewisian rocks **are** of Scourian age, there remain two important questions, firstly the presence of widespread metasediments in the Eastern Lewisian, particularly the eulysites and graphite schists, neither of which are found in the foreland Lewisian rocks, and secondly a problem of the persistent occurrence of Eastern Lewisian - type rocks seen as inliers within the Moine.

The geological survey (Peach *et al.*, 1910) initially made correlations between Glenelg and the rocks of South Harris. Rock (1987) suggests that all the marbles found within the Lewisian rocks, both in the foreland and within the Moine, probably have a similar origin, and that differences in bulk chemistry between different marble types are not related to their occurrence in either the foreland or within the Moine. Because unique metasediments do occur at Glenelg, and because only Eastern Lewisian - type rocks occur within the Moine east of Glenelg, it is thought that the Eastern Lewisian rocks may represent Lewisian age rocks that form the Moine basement and that the Western Lewisian, similar to the foreland, is indeed a slice of foreland Lewisian.

The continuous presence of a strip of highly deformed Moine between the two Lewisian types is highly important. Although the strip is composed of deformed rocks of probable Moine origin, it is possible that the D_1 - D_2 deformation only brought together two parcels of rock, the Western and Eastern Lewisian, that were already in close juxtaposition after D_0 deformation. Sutton and Watson (1962) suggested that the central strip of Moine opened out into a synform south of the Strathconon fault. The mapping of Barber and May (1975) suggests that whilst the strip of deformed Moine lies between the Eastern and Western Lewisian south of Loch Duich, north of Loch Duich the Eastern Lewisian is pinched out, and that the strip of Moine then cuts into the Western Lewisian, so that Western Lewisian rocks occur either side of it, emphasising that the presence of the strip between the two types of Lewisian rocks may well be coincidental. It is likely that the occurrence of foreland - type basement (the Western Lewisian) and "Moine" basement (the Eastern Lewisian) in close proximity is related to the occurrence of the Glenelg inlier immediately east of the Moine thrust, which separates metamorphosed cover from unmetamorphosed cover.

11.4 Origin of the eclogite

Unlike many eclogite - bearing terrains, such as the Caledonides of Norway, the origins and implications of eclogites are hard to interpret due to the lack of exposed area and due to the complicated post - eclogite history of the area. Norwegian eclogites, summarised by Griffin (1987), are at first sight similar to those at Glenelg, occurring as pods and lenses within amphibolite and granulite facies hosts. It has been demonstrated (e.g. Krogh, 1980) that the country rocks were also metamorphosed to eclogite facies and have since been retrogressed. However, some work (e.g. Austrheim and Griffin, 1985) has shown that eclogites occurred with hydration and deformation of pre - existing metamorphic country rocks during prograde metamorphism. The Glenelg eclogites are anhydrous, with hydration occurring later, causing the alteration of the eclogite. It is suggested that there are two periods of high grade metamorphism, but the relative ages of these two events are not known and there is no hard evidence within the Glenelg peninsular that would tie down the pre - eclogite facies history of the rocks, i.e. whether they may have been granulites (i.e. Scourian in age, but later re - metamorphosed) or basic igneous rocks.

11.5 Future work

In order to further constrain the age of the eclogites, dating of zircons and monazites within both the sediments and the basic igneous rocks may give older ages, backing up the hypothesis that the eclogites are of Scourian age, or at least proving a Lewisian parentage. Sm - Nd and Rb - Sr concentrates from garnet and clinopyroxene were obtained at East Kilbride although these have not yet been dated. The problems of Sm - Nd dating of polymetamorphosed rocks has already been highlighted, but the results would be more useful in conjunction with Rb - Sr. Because Rb - Sr dating has a much lower closure temperature than Sm - Nd, it would be interesting to see if the Rb - Sr ages were the same those measured by Sm - Nd. If so, and both were at $\approx$ 1000 Ma, it would be suggest that the age of peak Moine metamorphism (syn - D_2) was of that age, because there would have been no reasonably high temperature metamorphism since then to have reset the isotopic systems. If Rb - Sr gave 750 Ma or 450 Ma, then would suggest that reasonably high grade metamorphism of the Moine and Lewisian occurred later than 1000 Ma, and the eclogites might therefore have been Grenville in age.

At present the presence or absence of dykes within the Eastern Lewisian has not been proved at Glenelg, although Watson (1975) amongst others has suggested their presence in other inliers and May *et al.* (1993) has suggested their presence in the Eastern Lewisian north of Loch Duich. Much work might be put into tracking down better examples of possible dyke rocks and examining their field relationships. However, given the extreme state of later deformation within Eastern Lewisian rocks, it is possible that even if dykes were originally present, they would now exist in a completely unrecognisable state.

Structural mapping of the area in fine detail may help to identify any pre - Moine structures within the Lewisian, confirming that the Lewisian was uplifted prior to Moine deposition.

On the whole, the limited outcrop of the Lewisian at Glenelg has inevitably lead to somewhat sketchy details of the history of the area. Detailed re - investigation of other Lewisian outcrops further east within the Moine, in particular the Scardroy inlier, may well help to confirm or disprove the hypotheses presented in this thesis.

11.6 Conclusions

It has been suggested in this thesis that the Western and Eastern Lewisian rocks have suffered a common history since eclogite facies metamorphism. Discussion above suggests that this metamorphism may well have been Scourian in age. The history of the rocks is given below :

The earliest recognisable rocks of the Eastern Lewisian are metabasic nepheline - and olivine - normative rocks, now metamorphosed to produce garnet - bearing rocks, that coexist with a variety of metasediments. The original relationships between the two are not known. In the Western Lewisian quartz - normative basalts existed, apparently without related supracrustal rocks. After initial metamorphism, under dry conditions at

730°C, 15 Kb, both metasediments and meta - igneous rocks were intruded by quartzo - feldspathic melt, rich in alumina, that crystallised quartz, feldspar, Ca - rich garnet and kyanite. This might be correlated with the widespread production of felsic sheets in the Scourian of the foreland (e.g. Rollinson, 1994). In many rocks, there appears to have been reaction between the basic rock and acidic intrusion to produce either quartz - rich eclogite or amphibole - biotite - plagioclase stable with the eclogite facies minerals. Deformation (D_0) and recrystallisation followed the breakdown of anorthite within the quartz - kyanite streaks at ≈ 17 Kb, 780°C (Sanders, 1988, this thesis). The rocks were then uplifted, possibly with isothermal decompression to ≈ 10 Kb, with the partial breakdown of omphacite to form symplectites of diopside and plagioclase, and the alteration of kyanite to margarite - bearing assemblages. At some stage after the peak of metamorphism basic and ultrabasic dykes were intruded into the rocks.

After deposition of a series of pelites and quartzites, the Moine, onto the Lewisian rocks, the whole area was buried and subjected to further metamorphism and deformation. The effects of this metamorphism and deformation were variable, and throughout the area relicts of eclogite occur that remain unaffected by retrogression and deformation. The peak conditions of this metamorphism were during, or just after, D_2, at conditions of at least 8 Kb and ≈ 600 - 700°C. The first deformation event to affect both the Moine and Lewisian rocks (D_1) led to the formation of pods of eclogite around which the surrounding rocks were deformed in a ductile manner. During this deformation the Moine and Lewisian rocks were interleaved, the Western and Eastern Lewisian were brought together, and initial cross - cutting relationships both within the Lewisian between dykes and older rocks, and between the Lewisian and the Moine, were partly destroyed, leading to the sub - parallel banding of features now seen in the area (Ramsay, 1958, Sutton and Watson, 1959). During the second deformation (D_2) the area was partly hydrated and many rocks were retrogressed and deformed in a ductile manner, with the formation of schistose amphibole - plagioclase - garnet rocks. The eclogite pods remained metastable, and were deformed in a brittle manner, with cracks formed across them being filled by amphibole and plagioclase. Alteration within the eclogite pods was mostly restricted to the rims of these cracks. Also, large - scale sliding occurred in both the Moine and Eastern Lewisian, with strips of highly deformed rocks occurring, such as the central Moine strip. During the third deformation (D_3), probably of Caledonian age, some rocks were again hydrated and deformed in a ductile manner, but most suffered brittle deformation with the formation of cracks filled by epidote - amphibolite facies assemblages. The final deformation (D_4) lead to the cracking of the rocks once more. Microfaulting occurred along some of these faults.

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Appendices

APPENDIX 1

Sample numbers and localities

The localities of all samples metioned in the text are given below. All grid references are for grid square NG on 1:50,000 sheet 33.

Eastern Lewisian

Sample number	Grid reference	Description
5,7, 8	852160	Metapelite
10	854159	Kyanite - metapelite
27	883242	Marble nodule
40	837205	Amphibolite
46	835206	Marble nodule
56	852168	Marble nodule
71	835206	Calc - silicate
72	839202	Calc - silicate
80	839209	Amphibolite
83	839209	Quartz - rich eclogite
84	839209	Garnet - amphibolite
94, 95	839188	Eulysite
96	840179	Eclogite with QFK veins
98	834178	Metapelite
120	839202	Marble nodule
129	886234	Amphibolite
133	843211	Ultrabasic
203, 204	849168	Marble nodules
222	848210	Ultrabasic
223, 224, 342	853217	Orthopyroxene - bearing eclogite
228	855225	Eulysite
233	853224	QFK vein
237	837204	Eclogite
259, 260, 263	862236	Marble nodules
265	862236	Eclogite
271	870242	"Garnet - ite"

301, 302	892247	Websterite
310	896241	Metabasite
311 - 313	862236	Marble nodules
315 - 318	862236	Metapelites
329	885235	Pyroxenite
337 - 341, 217, 218	829161	Orthopyroxene - bearing eclogite
347, 350, 350b, 351	842216	Eclogite with QFK veins
353	842215	Quartz - rich eclogite
510	888233	Amphibolite
511	886234	Orthopyroxene - bearing eclogite
512	885235	Biotite - rich eclogite
BH	873254	Olivine - marble
C1 - C5	862236	Drilled cores in coarse garnet
Du4	891249	Mylonitised eclogite
E1 - E11	862236	Bimineralic eclogite
H4, H6, H9	888233	Amphibolite

Western Lewisian

1	782122	QF amphibolite
107, 108	768146	QF garnet - amphibolite
140, 144	785119	Folded plagioclase - amphibolite
208	766145	Plagioclase - amphibolite
246	769143	Biotite - rich amphibolite
252, 356	769142	Eclogite
257	771145	"Amphibolitite"
258	771145	"Amphibolitite"
358, 359, 361	768142	Plagioclase - amphibolite pods
364	771145	"Amphibolitite"
366	765145	Plagioclase - amphibolite
367	788117	"Amphibolitite"
370	791118	"Amphibolitite"
371	791118	Plagioclase - amphibolite
372	778124	Migmatite
373	778124	"Amphibolitite"
374	778122	Biotite - rich amphibolite
402	767139	QF rim to eclogite pod

410	769141	Eclogite
414 - 420	769142	Large eclogite pod
423	783119	Plagioclase - amphibolite
424, 425	786118	"Amphibolitite" cross cutting layer
429	786116	"Amphibolitite"
432	788116	"Amphibolitite"
446, 447	776122	Garnet - amphibolite
449	776122	Biotite - rich amphibolite
452	781122	Foliated plagioclase - amphibolite
456	769134	"Amphibolitite" pod
459	776124	Plagioclase - amphibolite pod
RC1	777122	"Amphibolitite" cross cutting layer
RC2, RC3	777122	Garnet - amphibolite

Moine

100	769151	Garnet - metapelite
A1	852098	Garnet - metapelite

APPENDIX II

Analytical Procedures

II.A Electron probe

Major element mineral analyses were obtained using the Cameca Camebax microprobe of the Department of Geology and Geophysics, University of Edinburgh. Uncovered thin sections were coated with a thin layer of carbon prior to analysis to prevent charge build up on the surface of the slide. Samples were positioned using a back - scattered electron imaging system built into the machine. Used in conjunction with the energy dispersive system rapid identification of phases could be achieved prior to obtaining quantative analyses.

Analyses were made using four wavelength dispersive spectrometers. Each element was measured for 30 seconds and background counts were measured for 15 seconds with a beam current of 20 nA and an accelerating potential of 20 kV, yealding a beam size of about 2 μm diameter. Due to problems with alkali mobility under the electron beam, feldspar, mica and pyroxene analyses were obtained wherever possible using a rastered beam covering about 10 μm. Count rates for the unknowns in the sample were compared to count rates for a set of known standards and corrected for matrix effects using the PAP correction, before being converted to oxide contents. Crystals used and standards for each element are given in table II.1.

Errors (2σ and percentage error, E) and detection limits (D.L.) can be calculated from a single analysis using the folowing equations :

$$2\sigma = 2W/[\sqrt{T_p}(\sqrt{R_p}-\sqrt{R_b})] \qquad E = 100/[\sqrt{T_p}(\sqrt{R_p}-\sqrt{R_b})] \qquad D.L. = (3W\sqrt{R_b})/(R_p\sqrt{T_b})$$

Where : T_p = peak count time; T_b = background count time; R_p = peak count rate; R_b = background count rate; W = wt % element

The errors and detection limits of analyses have been calculated for a representative analysis of each phase and are given in table II.2.

Table II.1. Standards and crystals used for the analysis of each element using the electron probe.

Element	Standard	Crystal
Na	jadeite	TAP
Mg	periclase	TAP
Al	corundum	TAP
Si	wollastonite	TAP
K	orthoclase	PET
Ca	wollastonite	PET
Ti	rutile	PET
Cr	Cr metal	LIF
Mn	Mn metal	LIF
Fe	Fe metal	LIF

TAP is thallium acid phthalate; PET is penta erythritol; LIF is lithium fluoride.

II.B Ion probe

Trace element contents of garnet, clinopyroxene and amphibole were measured using a Cameca ims 4f ion microprobe in the Department of Geology and Geophysics, University of Edinburgh. All samples were coated in a thin layer of gold prior to analysis to prevent charge build up on the surface of the slide. Analyses were performed by bombarding the sample with a beam of focused O^- ions. Secondary electrons sputtered from the surface of the sample are accelerated into a mass spectrometer. By varying the strength of the magnetic field in the spectrometer, ions of specific mass/charge ratios could be selected and counted using an electron multiplier. A primary beam current of 5 - 6 nA[1] was used, giving a beam spot of around 20 μm diameter.

For each element, one isotope was measured, usually the most abundant isotope, but occasionally other isotopes were chosen to minimise the effects of interference. A

[1] Analyses were obtained over a seven day period. For each day of operation the ion probe was recalibrated and slightly different beam currents were used for that days analyses.

Garnet	oxide	2 sigma	% error	D.L.
SiO2	38.267	0.0286	0.0374	0.0212
TiO2	0.030	0.0037	6.2316	0.0030
Al2O3	21.042	0.0208	0.0494	0.0173
Cr2O3	0.004	0.0060	75.1921	0.0010
FeO	25.410	0.0363	0.0715	0.0341
MnO	0.694	0.0088	0.6333	0.0243
MgO	6.424	0.0139	0.1079	0.0175
CaO	7.951	0.0133	0.0836	0.0160
Na2O	0.023	0.0044	9.6496	0.0049
K2O	0.004	0.0021	26.6208	0.0007
total	99.849			

Clinopyroxene	oxide	2 sigma	% error	D.L.
SiO2	52.193	0.0314	0.0301	0.0212
TiO2	0.191	0.0044	1.1396	0.0110
Al2O3	5.218	0.0110	0.1056	0.0157
Cr2O3	0.063	0.0060	4.7485	0.0113
FeO	7.968	0.0217	0.1361	0.0298
MnO	0.095	0.0053	2.7728	0.0127
MgO	11.002	0.0167	0.0759	0.0159
CaO	20.045	0.0205	0.0510	0.0166
Na2O	2.834	0.0129	0.2269	0.0225
K2O	0.014	0.0023	8.3571	0.0023
total	99.623			

Biotite	oxide	2 sigma	% error	D.L.
SiO2	38.394	0.0296	0.0386	0.0227
TiO2	2.999	0.0095	0.1578	0.0192
Al2O3	14.952	0.0185	0.0619	0.0244
Cr2O3	0.053	0.0060	5.6937	0.0024
FeO	10.357	0.0240	0.1159	0.0282
MnO	0.028	0.0052	9.3654	0.0054
MgO	18.202	0.0212	0.0582	0.0167
CaO	0.253	0.0039	0.7677	0.0113
Na2O	0.137	0.0050	1.8242	0.0137
K2O	9.458	0.0154	0.0812	0.0140
total	94.833			

Orthopyroxene	oxide	2 sigma	% error	D.L.
SiO2	56.138	0.0336	0.0299	0.0229
TiO2	0.010	0.0034	16.9727	0.0012
Al2O3	0.749	0.0055	0.3662	0.0144
Cr2O3	0.274	0.0076	1.3783	0.0218
FeO	10.985	0.0244	0.1108	0.0282
MnO	0.359	0.0071	0.9846	0.0205
MgO	31.183	0.0261	0.0419	0.0168
CaO	0.192	0.0035	0.9222	0.0101
Na2O	0.002	0.0038	93.9894	0.0005
K2O	0.008	0.0024	14.9007	0.0015
total	99.900			

Plagioclase	oxide	2 sigma	% error	D.L.
SiO2	59.918	0.0344	0.0287	0.0219
TiO2	0.013	0.0034	13.2688	0.0016
Al2O3	24.984	0.0211	0.0422	0.0169
Cr2O3	0.005	0.0050	49.6241	0.0015
FeO	0.006	0.0049	40.4557	0.0013
MnO	0.013	0.0041	15.6747	0.0033
MgO	0.014	0.0025	8.8217	0.0023
CaO	6.792	0.0126	0.0925	0.0148
Na2O	7.968	0.0254	0.1595	0.0218
K2O	0.144	0.0032	1.0959	0.0091
total	99.857			

Amphibole	oxide	2 sigma	% error	D.L.
SiO2	41.927	0.0295	0.0351	0.0220
TiO2	0.456	0.0051	0.5599	0.0148
Al2O3	13.282	0.0170	0.0641	0.0170
Cr2O3	0.070	0.0056	3.9815	0.0121
FeO	16.939	0.0300	0.0886	0.0294
MnO	0.117	0.0058	2.4782	0.0140
MgO	9.871	0.0164	0.0830	0.0165
CaO	11.523	0.0158	0.0686	0.0162
Na2O	2.174	0.0123	0.2837	0.0253
K2O	0.944	0.0055	0.2936	0.0124
total	97.303			

Epidote	oxide	2 sigma	% error	D.L.
SiO2	38.423	0.0282	0.0367	0.0216
TiO2	0.123	0.0041	1.6547	0.0088
Al2O3	27.377	0.0222	0.0406	0.0170
Cr2O3	0.011	0.0080	36.4462	0.0029
FeO	7.269	0.0206	0.1414	0.0270
MnO	0.230	0.0062	1.3519	0.0180
MgO	0.051	0.0031	3.0147	0.0057
CaO	23.850	0.0222	0.0465	0.0172
Na2O	0.015	0.0039	13.1656	0.0033
K2O	0.003	0.0022	36.4462	0.0005
total	97.352			

Chlorite	oxide	2 sigma	% error	D.L.
SiO2	27.033	0.0255	0.0472	0.0221
TiO2	0.030	0.0034	5.5937	0.0031
Al2O3	21.344	0.0223	0.0522	0.0189
Cr2O3	0.065	0.0052	3.9616	0.0194
FeO	17.950	0.0301	0.0840	0.0060
MnO	0.142	0.0058	2.0436	0.0152
MgO	21.172	0.0229	0.0540	0.1487
CaO	0.050	0.0029	2.8521	0.0052
Na2O	0.016	0.0037	11.5557	0.0037
K2O	0.087	0.0027	1.5642	0.0074
total	87.889			

maximum of 26 masses could be counted for any one analysis. For each mass the number of ions was counted for 5 seconds with an offset of about 75 eV, for ten cycles per analysis. Raw data was converted to deadtime - corrected, background - corrected counts per second. These were then corrected for isotopic abundance and mass interference.

II.C X - ray fluoresence spectrometry

Whole rock samples were prepared from the freshest samples available. The weathered rims of samples were cut of, and up to 300 g of sample was crushed to a size of 0.5 cm or less in a jaw crusher. These chips were then crushed in a Tema tungsten carbide gyromill for 1.5 minutes to a grain size of <200 μm.

The samples were dried overnight in an oven at 110°C. For major elements, measured quantities of lithium flux were added to previously ignited rock powder and the samples fused at 1100°C to obtain glass discs. The samples were analysed for 10 major elements (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K and P) on a Phillips PW 1480 wavelength dispersive sequential XRF spectrometer. For trace elements the samples were pressed into pellets under 10 tonnes pressure, and analysed for 17 trace elements () using the same spectrometer. Samples were calibrated using USGS and CRPG international standards. Further details of preparation procedure are given in Fitton *et al.* (1984) and Fitton and Dunlop (1985).

APPENDIX III

Representative bulk rock analyses

Tables III contains whole rock analyses and calculated CIPW NORM's for representative Eastern and Western Lewisian rocks. No analyses were made of Moine rocks. It includes representative analyses for Eastern Lewisian metapelites and marbles from May *et al.* (1993), selected analyses of Eastern Lewisian eclogites from Yoder and Tilley (1962), Alderman (1935) and O'Hara (1960), and analyses of Scourie dykes from Weaver and Tarney (1981). NORM's were calculated using the calculation in appendix 3 of Cox *et al.* (1979), using an estimated Fe'''/Fe'' ratio of 0.15.

TABLE III : Representative whole rock analyses
Eastern Lewisian

	Bimineralic eclogite							Qtz Ec.		Opx Ec.	
	E5	E6	E8	E10	E11	E2	E1	83	96	511	223
SiO2	48.91	47.57	46.08	47.29	47.69	47.34	47.80	47.69	51.88	48.93	48.70
TiO2	0.82	1.13	0.93	0.80	0.88	0.82	0.83	1.72	0.74	0.59	0.62
Al2O3	12.64	13.61	14.98	13.95	13.61	15.29	14.28	17.56	16.99	9.31	12.84
Fe2O3	10.75	12.38	14.12	12.64	12.41	11.69	12.41	14.92	9.07	9.57	13.52
FeO											
MnO	0.23	0.27	0.33	0.28	0.27	0.33	0.25	0.20	0.34	0.17	0.17
MgO	10.09	10.04	9.93	9.95	9.99	9.03	9.36	5.15	6.17	14.87	14.33
CaO	14.01	13.09	12.28	13.06	13.32	12.46	12.70	10.77	9.62	14.15	7.34
Na2O	2.84	2.50	2.16	2.38	2.56	2.67	2.42	1.67	3.20	1.29	1.20
K2O	0.07	0.16	0.09	0.06	0.06	0.18	0.16	0.35	0.52	0.17	0.44
P2O5	0.02	0.03	0.01	0.02	0.05	0.05	0.07	0.12	0.05	0.07	0.05
LOI	-0.24	-0.27	-0.58	-0.43	-0.04	0.70	-0.04	-0.56	0.28	0.68	0.73
Total	**100.1**	**100.5**	**100.3**	**100.0**	**100.8**	**100.6**	**100.2**	**99.6**	**98.9**	**99.8**	**99.9**
FeO	9.67	11.14	12.71	11.37	11.17	10.52	11.17	13.43	8.16	8.61	12.17
Mg No.	0.51	0.47	0.44	0.47	0.47	0.46	0.46	0.28	0.43	0.63	0.54
Ba	15.2	23.4	20.9	15.2	7.7	46.7	36.3	133.5	470.6	107.8	253.5
Rb	1.1	0.7	1.7	0.6	0.2	1.4	1.2	2.8	5.3	2.0	4.4
Th	1.5	0.0	3.1	1.4	1.5	0.4	0.0	0.4	0.0	1.0	0.2
Nb	2.7	4.5	3.6	2.8	3.2	3.1	3.3	6.6	1.2	0.9	2.5
La	5.3	3.4	1.5	0.0	2.2	2.0	10.4	6.5	6.2	1.5	9.5
Ce	6.7	13.9	0.0	5.0	9.3	9.9	34.6	37.8	31.2	6.8	30.4
Sr	132.7	127.3	101.7	117.9	126.3	140.7	143.9	229.5	647.4	126.3	278.2
Nd	5.4	8.7	2.5	5.0	6.3	5.8	13.6	17.5	9.3	7.5	11.2
Zr	31.2	45.2	33.1	32.3	33.6	31.0	36.4	68.3	32.0	35.2	53.6
Y	16.2	18.6	20.8	18.7	17.4	16.9	17.6	27.3	11.0	16.1	12.3
Sc	47.2	49.4	47.1	46.4	54.6	51.9	45.4	40.0	36.2	62.2	27.0
V	338.2	325.6	287.2	312.1	306.8	273.0	279.7	411.6	189.9	295.8	149.9
Cr	624.1	585.1	568.7	568.7	608.9	211.1	587.4	93.3	189.1	1395.6	234.7
Ni	90.2	144.7	105.6	91.2	141.4	147.6	151.7	61.5	35.0	223.2	221.8
Cu	80.5	227.0	147.3	80.2	184.4	60.3	203.0	41.9	27.2	29.0	48.1
Zn	48.3	48.8	47.9	48.2	48.8	55.8	54.6	109.9	74.4	62.5	132.5
Pb	0.0	0.0	0.9	0.0	0.2	1.3	0.3	1.2	4.1	2.1	1.7
CIPW NORM's (assuming FeO = 85% Fe(tot))											
qtz	-	-	-	-	-	-	-	1.11	0.04	-	-
cor	-	-	-	-	-	-	-	-	-	-	-
orth	0.41	0.96	0.55	0.35	0.33	1.04	0.94	2.08	3.08	1.02	2.60
alb	16.91	16.19	15.34	16.34	16.13	17.98	18.78	14.11	27.05	10.90	10.14
an	21.51	25.40	30.87	27.17	25.45	29.18	27.60	39.33	30.42	19.08	28.31
neph	3.84	2.68	1.58	2.05	2.98	2.49	0.91	-	-	-	-
diop	38.89	32.17	24.59	30.67	33.09	26.62	28.90	11.80	14.18	40.91	6.56
hyp	-	-	-	-	-	-	-	24.09	19.79	7.50	38.24
ol	14.18	17.69	22.20	18.73	17.61	17.63	17.99	-	-	11.02	5.73
mag	2.14	2.46	2.81	2.52	2.47	2.33	2.47	2.97	1.80	1.90	2.69
ilm	1.56	2.15	1.76	1.51	1.67	1.56	1.58	3.26	1.41	1.11	1.18
ap	0.04	0.07	0.03	0.05	0.10	0.11	0.14	0.26	0.11	0.15	0.11

TABLE III (cont.)

	My	"Grt"	Bt	Published Analyses				Amphibolite			
	Du4		512	Y&T	Y&T	Ald.	O'Hara	81	H6	82	310
SiO2	49.95	40.60	50.75	50.05	42.60	51.01	44.90	47.00	49.88	47.67	50.91
TiO2	0.90	0.09	1.55	1.55	3.84	1.01	2.00	1.29	1.55	1.74	1.40
Al2O3	15.25	17.30	13.88	13.37	12.41	15.02	9.00	15.70	7.05	17.01	13.76
Fe2O3	12.83	21.20	16.89	3.71	3.50	2.29	3.20	13.17	12.41	15.04	14.11
FeO				10.39	16.94	10.01	14.70				
MnO	0.23	1.04	0.19	0.25	0.36	0.22	0.30	0.20	0.12	0.22	0.22
MgO	6.61	9.00	8.77	6.49	7.23	6.30	14.20	7.25	15.19	4.87	6.66
CaO	9.92	9.30	4.78	11.00	11.18	11.32	9.70	11.65	10.93	11.12	10.50
Na2O	3.05	1.80	1.93	2.38	1.09	2.17	1.00	1.86	1.24	1.63	1.40
K2O	0.64	0.01	1.30	0.36	0.15	0.06	0.20	0.34	0.39	0.32	0.48
P2O5	0.10		0.17					0.10	0.02	0.15	0.09
LOI	0.62		-0.27					1.19	1.27	0.39	1.06
Total	**100.1**	**100.3**	**99.9**	**99.6**	**99.3**	**99.4**	**99.2**	**99.8**	**100.0**	**100.2**	**100.6**
FeO	11.55		15.20					11.85	11.17	13.53	12.70
Mg No.	0.36		0.37	0.32	0.26	0.34	0.45	0.38	0.58	0.26	0.34
Ba	197.7		333.7					64.7	21.0	89.6	102.8
Rb	8.6		22.6					2.3	1.8	1.7	1.8
Th	0.8		4.7					0.2	0.3	1.1	0.9
Nb	5.9		6.2					4.3	6.1	7.5	5.3
La	7.1		3.6					7.0	5.5	8.8	9.6
Ce	17.9		11.8					11.5	10.0	27.8	17.6
Sr	229.7		95.9					140.0	16.0	196.9	167.6
Nd	7.9		13.9					4.2	9.9	17.4	6.7
Zr	47.8		92.3					48.7	82.3	78.5	53.6
Y	20.8		25.6					23.8	20.4	33.9	19.9
Sc	51.5		34.0					45.9	32.9	45.3	54.0
V	310.1		333.1					342.6	268.1	377.8	326.2
Cr	340.7		212.3					270.5	1531.4	93.3	102.7
Ni	126.6		126.6					108.7	509.2	59.0	82.8
Cu	135.0		292.6					58.0	9.9	37.1	20.5
Zn	121.3		93.8					113.5	28.9	106.2	165.0
Pb	4.7		3.2					1.8	1.5	0.9	3.7
CIPW NORM's (assuming FeO = 85% Fe(tot))											
qtz	-	-	2.54	1.68	-	2.99	-	-	-	1.68	5.72
cor	-	-	0.98	-	-	-	-	-	-	-	-
orth	3.79	0.06	7.71	2.13	0.89	0.35	1.18	1.99	2.30	1.89	2.84
alb	25.78	15.21	16.31	20.11	9.21	18.34	8.45	15.72	10.48	13.78	11.83
an	26.00	39.05	22.65	24.70	28.49	31.03	19.45	33.46	12.50	38.11	29.81
neph	-	-	-	-	-	-	-	-	-	-	-
diop	19.19	5.67	-	24.59	22.49	20.78	23.34	20.04	33.49	14.30	18.45
hyp	9.44	9.71	41.45	18.01	15.86	20.68	18.67	13.56	27.49	22.28	24.13
ol	6.69	8.22	-	-	6.75	-	13.52	5.11	4.19	-	-
mag	2.55	0.69	3.36	5.38	5.08	3.32	4.64	2.62	2.47	2.99	2.81
ilm	1.71	0.17	2.94	2.95	7.30	1.92	3.80	2.46	2.94	3.31	2.66
ap	0.22	-	0.36					0.22	0.04	0.33	0.20

for published analyses :

Y & T : Yoder and Tilley (1962) SN.'s 35090 and 35083 respectively

Ald. : Alderman (1935) SN. G.12

O'Hara : O'Hara (1960) SN. G.8

TABLE III (cont.)

	Marble nod.		Metaseds. (from May et al.) Pelites		Marbles		
	260	313	S13250	S7937	S72689	S72693	(Rodil)
SiO2	51.00	46.46	56.40	59.10	9.60	11.88	13.20
TiO2	2.19	0.55	1.06	1.08	0.03	0.09	
Al2O3	12.64	10.98	18.88	17.78	0.31	1.15	1.46
Fe2O3	22.17	5.87	11.84	10.57	0.55	1.63	2.31
FeO							
MnO	0.30	0.33	0.09	0.09	0.08	0.15	0.11
MgO	4.11	11.57	5.30	5.91	21.01	18.94	18.74
CaO	2.81	23.59	2.21	1.59	31.13	31.74	33.82
Na2O	3.31	0.55	0.84	0.66	0.01	0.06	
K2O	1.42	0.03	2.63	3.00	0.10	0.43	
P2O5	0.04	0.33	0.01	0.11		0.05	0.26
LOI	-1.07	0.23			36.51	32.80	30.00
Total	**98.9**	**100.5**	**99.3**	**99.9**	**99.3**	**98.9**	**99.9**
FeO	19.95	5.28					
Mg No.	0.17	0.69					
Ba	229.8	5.7	546.0	756.0	20.0	120.0	
Rb	26.4	0.5	96.0	105.0	5.0	12.0	
Th	4.5	1.5					
Nb	12.7	2.9	12.0	8.0			
La	4.4	5.4					
Ce	20.3	11.0	60.0	43.0	10.0		
Sr	55.1	12.7	203.0	167.0	46.0	53.0	
Nd	5.7	9.0					
Zr	95.7	116.3	102.0	109.0	2.0	7.0	
Y	35.4	22.9	28.0	23.0	1.0	4.0	
Sc	63.9	14.5					
V	290.1	129.1	253.0	252.0		10.0	
Cr	304.8	75.9	236.0	240.0		10.0	
Ni	120.2	44.1	120.0	89.0		5.0	
Cu	17.7	25.7	79.0	57.0		9.0	
Zn	86.7	22.3	145.0	172.0	3.0	9.0	
Pb	2.8	1.3	16.0	11.0		1.0	

CIPW NORM's (assuming FeO = 85% Fe(tot))

qtz	2.43
cor	0.63
orth	8.38
alb	27.97
an	13.70
neph	-
diop	-
hyp	36.22
ol	-
mag	4.41
ilm	4.15
ap	0.08

TABLE III (cont.)

Western Lewisian

	Eclogite pod							Gran	Gnt amph.	
	414	415	416	417	418	419	420	306	RC3	446
SiO2	52.97	52.53	54.80	50.63	51.12	50.87	51.13	49.05	52.17	49.00
TiO2	0.98	1.07	1.01	1.15	1.15	1.18	1.20	1.32	3.58	4.13
Al2O3	13.74	13.44	15.39	13.68	13.52	13.68	13.73	15.33	12.08	13.05
Fe2O3	13.29	13.55	9.94	14.31	13.97	14.42	14.56	14.03	14.70	14.05
FeO										
MnO	0.21	0.21	0.16	0.23	0.21	0.23	0.23	0.24	0.22	0.22
MgO	5.44	5.94	5.90	6.71	6.68	6.73	6.73	5.59	3.95	4.78
CaO	8.01	8.28	7.47	10.55	10.23	10.45	10.54	12.36	9.22	10.83
Na2O	2.82	2.41	3.21	2.81	2.15	2.23	2.00	1.32	2.85	1.99
K2O	1.35	1.21	1.30	0.52	0.58	0.51	0.40	0.19	0.68	0.88
P2O5	0.10	0.10	0.17	0.12	0.12	0.12	0.12	0.10	0.43	0.44
LOI	1.32	1.27	1.04	-0.26	-0.03	-0.27	-0.24	0.77	0.57	0.73
Total	**100.2**	**100.0**	**100.4**	**100.4**	**99.7**	**100.1**	**100.4**	**100.3**	**100.4**	**100.1**
FeO	11.96	12.19	8.94	12.88	12.57	12.98	13.10	12.62	13.23	12.64
Mg No.	0.31	0.33	0.40	0.34	0.35	0.34	0.34	0.31	0.23	0.27
Ba	210.2	164.1	275.1	127.3	174.5	150.2	120.2	52.2	120.6	220.3
Rb	21.5	18.2	29.0	11.1	14.6	13.5	9.2	2.9	7.6	12.9
Th	2.0	1.6	2.0	2.3	2.3	2.1	2.1	1.2	1.8	3.3
Nb	16.8	13.2	10.5	8.0	8.7	9.1	9.0	2.8	17.9	19.1
La	5.4	7.6	13.9	4.5	7.3	12.6	7.0	0.0	22.1	14.6
Ce	23.3	19.1	37.1	18.2	25.7	23.2	27.3	11.8	56.7	52.7
Sr	164.9	139.8	248.6	122.9	166.3	137.0	140.5	115.5	144.9	209.5
Nd	8.4	7.9	21.3	7.5	17.4	10.7	8.7	7.1	34.9	32.6
Zr	70.8	72.3	130.5	76.3	73.2	76.0	78.0	44.2	174.0	190.7
Y	28.8	21.1	34.7	23.9	23.0	24.2	24.4	24.40	33.9	37.1
Sc	45.4	45.8	34.4	49.3	55.5	47.7	57.0	54.50	22.3	27.3
V	272.3	283.3	208.1	313.3	322.2	318.7	307.9	359.30	349.4	352.8
Cr	107.2	111.8	137.0	130.5	127.0	128.2	126.5	298.70	32.6	33.5
Ni	58.9	70.7	112.7	87.5	90.2	88.2	85.4	142.90	52.9	76.6
Cu	19.9	12.2	8.7	98.1	173.2	102.1	119.6	122.30	57.6	20.1
Zn	128.4	132.6	106.9	117.1	114.0	118.2	115.0	110.50	119.9	103.0
Pb	7.3	4.9	5.0	3.3	6.4	2.5	4.0	16.60	2.5	8.0
CIPW NORM's (assuming FeO = 85% Fe(tot))										
qtz	2.81	3.85	3.90	-	2.29	1.21	2.75		7.04	4.64
cor	-	-	-	-	-	-	-		-	-
orth	8.00	7.18	7.70	3.07	3.42	3.00	2.34		4.00	5.21
alb	23.83	20.37	27.13	23.75	18.17	18.85	16.90		24.09	16.82
an	20.80	22.23	23.70	23.15	25.50	25.78	27.28		18.15	24.04
neph	-	-	-	-	-	-	-		-	-
diop	15.77	15.65	10.97	24.18	20.91	21.59	20.73		23.10	24.57
hyp	21.97	23.47	21.04	14.84	23.18	23.52	24.09		12.09	11.82
ol	-	-	-	3.63	-	-	-		-	-
mag	2.64	2.70	1.98	2.85	2.78	2.87	2.90		2.93	2.80
ilm	1.85	2.04	1.92	2.18	2.19	2.25	2.29		6.80	7.85
ap	0.22	0.23	0.36	0.26	0.26	0.25	0.27		0.94	0.97

TABLE III (cont.)

	Pl amph.					Bt	"Hbl - ite"			"Act - ite"		
	423	358	469	258	434A	374	424	373	RC1	429	432	367
SiO2	42.46	49.65	48.03	55.71	47.78	50.36	42.48	45.08	47.39	48.31	49.84	51.81
TiO2	4.51	1.03	1.45	0.49	0.64	4.30	4.38	0.51	0.40	0.52	0.23	0.15
Al2O3	7.21	13.93	14.97	15.14	14.63	12.65	7.17	11.23	10.04	8.80	7.45	5.38
Fe2O3	17.89	13.47	13.51	7.99	12.77	12.86	17.86	18.19	17.16	11.45	10.78	8.67
FeO												
MnO	0.25	0.20	0.19	0.13	0.19	0.18	0.25	0.30	0.24	0.19	0.24	0.20
MgO	9.95	7.00	7.37	7.64	8.47	4.97	10.01	10.45	11.05	16.15	16.92	20.02
CaO	13.31	9.89	10.46	6.33	10.29	10.05	12.93	10.85	10.44	9.05	10.22	10.45
Na2O	1.16	2.79	2.24	3.55	2.97	0.48	0.99	1.72	1.51	0.82	0.75	0.77
K2O	0.76	0.89	0.73	1.62	0.46	2.73	0.74	1.12	0.64	2.61	1.46	0.08
P2O5	0.76	0.09	0.14	0.13	0.04	0.34	0.55	0.01	0.03	0.07	0.01	0.01
LOI	0.92	1.26	1.08	1.41	0.96	1.21	1.76	0.81	0.85	1.80	1.96	2.87
Total	**99.2**	**100.2**	**100.2**	**100.1**	**99.2**	**100.1**	**99.1**	**100.3**	**99.8**	**99.8**	**99.9**	**100.4**
FeO	16.10	12.12	12.16	7.19	11.49	11.57	16.07	16.37	15.44	10.30	9.70	7.80
Mg No.	0.38	0.37	0.38	0.52	0.42	0.30	0.38	0.39	0.42	0.61	0.64	0.72
Ba	230.4	138.7	113.2	484.6	149.2	1144.5	37.2	102.5	77.1	1115.0	436.2	15.2
Rb	17.3	13.0	11.0	39.3	2.8	78.3	3.9	8.9	8.1	53.3	21.4	0.8
Th	3.7	0.5	1.8	2.6	0.0	5.7	5.3	1.9	1.9	5.0	1.1	0.0
Nb	8.3	2.8	6.4	3.7	3.4	20.0	103.2	1.4	2.0	3.3	1.3	1.6
La	12.4	1.6	8.2	13.6	6.2	17.8	43.5	0.0	7.7	7.3	2.5	2.4
Ce	39.2	17.6	17.3	24.8	32.4	58.5	118.3	16.0	17.1	15.0	3.7	9.7
Sr	210.1	182.5	170.9	396.3	601.0	328.7	86.1	24.8	21.3	47.4	22.5	22.0
Nd	18.1	7.7	9.3	15.1	9.3	25.0	58.1	2.0	3.1	7.7	0.0	4.3
Zr	105.2	53.9	76.8	93.2	41.5	141.0	283.3	16.1	36.0	49.6	15.9	9.8
Y	29.2	16.4	22.7	13.3	16.6	29.5	17.3	6.4	9.0	13.8	12.2	1.9
Sc	43.4	41.1	42.9	23.4	50.1	16.1	39.6	29.3	23.8	28.7	30.6	23.5
V	401.0	312.8	398.1	126.7	267.1	352.2	329.6	318.6	238.4	189.3	154.7	72.8
Cr	53.6	115.1	269.4	319.0	358.0	42.7	437.1	1662.4	1756.2	2204.4	2340.4	2475.7
Ni	42.6	110.1	121.1	225.6	185.4	97.0	145.9	333.4	430.8	617.7	576.0	1260.1
Cu	139.0	31.9	15.0	10.8	19.7	13.9	645.3	15.1	15.5	10.4	18.6	15.0
Zn	136.7	142.1	125.8	109.7	128.4	123.9	144.4	192.7	161.8	199.3	220.0	133.8
Pb	8.4	5.3	5.1	7.7	8.2	8.6	2.9	0.5	1.5	1.4	0.0	0.0
CIPW NORM's (assuming FeO = 85% Fe(tot))												
qtz	-	-	-	1.70	-	9.07	-	-	-	-	-	-
cor	-	-	-	-	-	-	-	-	-	-	-	-
orth	4.48	5.28	4.32	9.58	2.72	16.13	4.37	6.65	3.76	15.41	8.62	0.47
alb	7.41	23.58	18.93	30.00	24.04	4.06	8.37	10.26	12.76	6.93	6.34	6.51
an	12.21	22.82	28.60	20.56	25.20	24.26	12.92	19.57	18.72	12.60	12.63	10.98
neph	1.30	-	-	-	0.57	-	-	2.32	-	-	-	-
diop	43.93	21.67	19.18	8.80	21.20	21.04	41.81	28.25	27.17	25.91	30.49	32.48
hyp	-	10.23	12.14	24.77	-	12.19	1.60	-	15.09	8.01	22.00	39.90
ol	14.53	6.46	6.27	-	19.62	-	9.84	26.28	10.74	17.24	9.96	3.12
mag	3.56	2.68	2.69	1.59	2.54	2.56	3.55	3.62	3.41	2.28	2.15	1.73
ilm	8.57	1.95	2.75	0.92	1.22	8.17	8.32	0.97	0.77	0.98	0.44	0.28
ap	1.67	0.20	0.31	0.28	0.09	0.75	1.21	0.02	0.07	0.16	0.03	0.03

APPENDIX IV

Representative mineral analyses

Representative mineral analyses of **garnets**, **clinopyroxenes** and **amphiboles** for the rocks discussed in the thesis are given in the following tables. Tables IV.i - iii are for Eastern Lewisian basic rocks, garnets, clinopyroxenes and amphiboles respectively. Tables IV.iv & v are for garnets and clinopyroxenes respectively from Eastern Lewisian metasedimentary rocks. Tables IV.vi - viii are for garnets, clinoyproxenes and amphiboles respectively from Western Lewisian rocks.

Important differences in chemistry within other phases are mentioned in the text, and, generally speaking, do not involve the complex substitutions seen in the amphiboles and clinopyroxenes. The compositions of the more variable of these phases are briefly described below :

Orthopyroxene occurs in some Eastern Lewisian eclogites and within one marble nodule. It is normally of 75 - 80% enstatite, although in the marble nodule it is only 45% enstatite.

Plagioclase in metabasic rocks is usually oligoclase (An_{10-30}), but garnet often alters to more Ca - feldspar of An_{55-65}. In quartz - feldspar - kyanite veins it is of highly variable composition, given in the text where relevant. In the metasediments, plagioclase is either of approximately An_{26-42} or An_{2-8}.

Biotite in the metabasic rocks is usually of about 3 wt% TiO_2, and Mg no. of about 0.55 - 0.60. In sediments the Ti content is usually lower, about 0.7 - 2.0 wt%, but in one group of rocks it is 2.4 - 4.1 wt%. The Mg no. is about 0.55 - 0.65 in the former, 0.4 - 0.45 in the latter. In the marbles, biotite is usually almost pure phlogopite end - member.

TABLE IV.i : Representative analyses - E. Lewisian Grt

Bimineralic Eclogite

	E5/3 core	E10/ip1 core	E2/5 core	E9/2 core	E3/5 alt	E1/4 alt	E9/D v rim	353/1B core	353/4A rim	353/H qtz agg.
SiO2	38.90	38.92	38.89	38.66	38.60	39.17	38.84	39.12	38.88	39.24
TiO2	0.11	0.06	0.05	0.07	0.07	0.07	0.06	0.09	0.05	0.06
Al2O3	21.52	21.38	21.64	21.62	21.09	21.53	21.83	20.90	21.07	21.77
Cr2O3	0.10	0.08	0.03	0.08	0.24	0.10	0.07	0.10	0.06	0.01
FeO	20.93	21.33	20.82	20.06	21.37	20.30	21.35	20.50	22.02	20.41
MnO	0.60	0.67	0.85	0.83	0.79	0.47	1.01	0.44	0.52	0.38
MgO	8.96	8.67	7.57	8.60	7.80	8.91	7.85	9.25	8.30	8.86
CaO	8.49	8.26	10.03	9.38	9.14	8.68	9.13	8.95	8.46	8.64
Total	99.64	99.42	99.91	99.33	99.13	99.27	100.16	99.37	99.40	99.38
Si	2.97	2.98	2.97	2.95	2.98	2.99	2.96	2.98	2.99	2.99
Al(iv)	0.03	0.02	0.03	0.05	0.02	0.01	0.04	0.02	0.01	0.01
Al(vi)	1.90	1.91	1.92	1.90	1.89	1.93	1.92	1.87	1.90	1.95
Ti	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe'''	0.12	0.10	0.10	0.13	0.11	0.06	0.10	0.13	0.11	0.05
Cr	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.00
Fe''	1.22	1.27	1.23	1.15	1.27	1.24	1.26	1.17	1.31	1.26
Mn	0.04	0.04	0.06	0.05	0.05	0.03	0.07	0.03	0.03	0.02
Mg	1.02	0.99	0.86	0.98	0.90	1.01	0.89	1.05	0.95	1.01
Ca	0.69	0.68	0.82	0.77	0.76	0.71	0.75	0.73	0.70	0.71
Mg no.	0.45	0.44	0.41	0.46	0.41	0.45	0.41	0.47	0.42	0.45
Alm.	**41.06**	**42.56**	**41.50**	**39.00**	**42.75**	**41.32**	**42.49**	**39.34**	**43.74**	**41.94**
Spess.	**1.30**	**1.47**	**1.85**	**1.81**	**1.73**	**1.02**	**2.21**	**0.95**	**1.13**	**0.82**
Pyrope	**34.28**	**33.21**	**29.01**	**33.16**	**30.13**	**33.92**	**30.13**	**35.21**	**31.82**	**33.65**
Gross.	**17.36**	**17.64**	**22.71**	**19.40**	**19.39**	**20.41**	**19.89**	**17.56**	**17.72**	**21.23**
Uv.	**0.30**	**0.24**	**0.10**	**0.22**	**0.74**	**0.29**	**0.21**	**0.30**	**0.18**	**0.02**
Andr.	**5.69**	**4.88**	**4.82**	**6.40**	**5.25**	**3.05**	**5.07**	**6.64**	**5.40**	**2.34**

from Bimineralic eclogite profiles

	353/A/1 core	353/A/9 rim	353/B/11 core	353/B/1 rim	E2/A/1 core	E2/A/27 rim	E6/A/2 core	E6/A/33 rim	E9/A/2 core	E9/A/25 rim
SiO2	38.67	38.63	38.93	38.26	38.76	38.08	38.58	37.97	38.76	38.34
TiO2	0.09	0.05	0.08	0.05	0.08	0.95	0.07	0.05	0.08	0.05
Al2O3	21.63	21.39	21.67	21.40	21.64	21.60	21.67	21.25	21.63	21.59
Cr2O3	0.02	0.10	0.01	0.01	0.04	0.03	0.06	0.04	0.10	0.07
FeO	20.75	21.65	20.48	24.41	20.19	22.25	21.61	24.08	20.45	21.11
MnO	0.52	0.47	0.49	0.45	0.73	1.02	0.72	0.98	0.86	1.04
MgO	8.75	8.23	8.97	6.11	8.54	6.96	8.96	6.66	8.83	8.17
CaO	8.66	8.54	8.98	9.07	9.85	9.57	8.21	8.38	9.16	9.07
Total	99.18	99.18	99.65	99.82	99.86	100.47	99.91	99.46	99.89	99.46
Si	2.96	2.97	2.96	2.96	2.95	2.92	2.94	2.95	2.95	2.94
Al(iv)	0.04	0.03	0.04	0.04	0.05	0.08	0.06	0.05	0.05	0.06
Al(vi)	1.91	1.91	1.90	1.92	1.89	1.87	1.88	1.89	1.88	1.89
Ti	0.01	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00
Fe'''	0.12	0.12	0.12	0.11	0.15	0.10	0.17	0.15	0.15	0.16
Cr	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Fe''	1.21	1.27	1.18	1.47	1.13	1.32	1.20	1.41	1.15	1.19
Mn	0.03	0.03	0.03	0.03	0.05	0.07	0.05	0.06	0.06	0.07
Mg	1.00	0.94	1.02	0.71	0.97	0.79	1.02	0.77	1.00	0.93
Ca	0.71	0.70	0.73	0.75	0.80	0.79	0.67	0.70	0.75	0.74
Mg no.	0.45	0.42	0.46	0.32	0.46	0.37	0.46	0.35	0.47	0.44
Alm.	**41.02**	**43.22**	**39.84**	**49.73**	**38.33**	**44.59**	**41.00**	**47.94**	**38.88**	**40.58**
Spess.	**1.14**	**1.03**	**1.07**	**0.99**	**1.60**	**2.23**	**1.58**	**2.18**	**1.88**	**2.30**
Pyrope	**33.80**	**31.93**	**34.36**	**23.83**	**32.83**	**26.73**	**34.61**	**26.19**	**33.93**	**31.77**
Gross.	**18.23**	**17.81**	**18.58**	**20.01**	**19.58**	**21.22**	**14.28**	**16.09**	**17.50**	**17.33**
Uv.	**0.06**	**0.28**	**0.02**	**0.04**	**0.12**	**0.09**	**0.17**	**0.12**	**0.29**	**0.20**
Andr.	**5.75**	**5.72**	**6.12**	**5.40**	**7.55**	**5.14**	**8.36**	**7.48**	**7.52**	**7.82**

TABLE IV.i (cont)

	Coarse Grt.		Biotite Ec.		Orthopyroxene Ec.			
	C1/C	C1/1	512/7	512/5	511/2	511/4	511/11	223/i
	core	v rim	core	rim	cpx	opx	qtz agg.	core
SiO2	38.16	37.31	38.68	37.97	39.61	39.68	39.65	39.48
TiO2	0.08	0.02	0.05	0.07	0.03	0.02	0.02	0.15
Al2O3	20.86	20.84	21.70	21.10	22.10	21.93	22.09	22.05
Cr2O3	0.03	0.01	0.03	0.04	0.17	0.41	0.00	0.03
FeO	25.12	29.22	25.87	28.27	19.24	19.17	18.35	19.58
MnO	1.22	1.94	0.41	0.52	0.52	0.55	0.44	0.34
MgO	7.72	5.62	9.84	7.70	12.87	12.58	12.78	11.52
CaO	6.16	4.15	3.44	3.88	5.00	5.49	6.15	6.41
Total	99.39	99.12	100.01	99.59	99.55	99.83	99.47	99.57
Si	2.96	2.96	2.96	2.96	2.96	2.97	2.96	2.97
Al(iv)	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.03
Al(vi)	1.87	1.91	1.91	1.90	1.91	1.90	1.91	1.93
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Fe'''	0.15	0.13	0.12	0.14	0.11	0.11	0.13	0.09
Cr	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.00
Fe''	1.48	1.81	1.53	1.70	1.09	1.09	1.02	1.15
Mn	0.08	0.13	0.03	0.03	0.03	0.03	0.03	0.02
Mg	0.89	0.66	1.12	0.89	1.43	1.40	1.42	1.29
Ca	0.51	0.35	0.28	0.32	0.40	0.44	0.49	0.52
Mg no.	0.38	0.27	0.42	0.34	0.57	0.56	0.58	0.53
Alm.	**49.86**	**61.22**	**51.70**	**57.66**	**36.92**	**36.76**	**34.42**	**38.51**
Spess.	**2.71**	**4.40**	**0.90**	**1.16**	**1.10**	**1.17**	**0.93**	**0.73**
Pyrope	**30.15**	**22.47**	**37.88**	**30.24**	**48.44**	**47.24**	**48.03**	**43.40**
Gross.	**9.61**	**5.61**	**3.34**	**4.07**	**7.61**	**8.32**	**10.40**	**13.06**
Uv.	**0.08**	**0.02**	**0.07**	**0.13**	**0.49**	**1.19**	**0.00**	**0.08**
Andr.	**7.58**	**6.29**	**6.10**	**6.75**	**5.43**	**5.30**	**6.22**	**4.22**

	Orthopyroxene Ec. (cont)						from profiles			
	223/iv	337/2	337/8	217/i	338/6	340/2	223/A/13	223/A/1	223/B/9	223/B/1
	rim	core	rim		core	rim	core	rim	core(QFK	rim(QFK)
SiO2	39.94	39.26	38.86	39.15	39.25	38.30	39.57	39.49	39.34	39.51
TiO2	0.01	0.09	0.03	0.01	0.04	0.04	0.06	0.03	0.06	0.04
Al2O3	22.25	21.62	21.22	21.91	21.82	21.40	22.13	22.00	21.93	22.32
Cr2O3	0.02	0.15	0.16	0.01	0.04	0.02	0.05	0.04	0.02	0.01
FeO	20.18	21.26	23.10	22.10	20.53	22.89	18.85	20.30	20.18	19.36
MnO	0.32	0.44	0.54	0.72	0.37	0.48	0.31	0.37	0.32	0.28
MgO	12.22	11.40	9.91	10.62	10.72	6.43	12.40	12.26	11.25	11.95
CaO	4.68	5.37	5.47	4.74	7.06	10.04	5.67	4.59	5.92	5.81
Total	99.68	99.63	99.32	99.28	99.85	99.62	99.08	99.11	99.04	99.30
Si	2.99	2.97	2.98	2.98	2.96	2.96	2.97	2.98	2.98	2.97
Al(iv)	0.01	0.03	0.02	0.02	0.04	0.04	0.03	0.02	0.02	0.03
Al(vi)	1.96	1.89	1.89	1.95	1.90	1.91	1.94	1.94	1.94	1.95
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe'''	0.04	0.12	0.12	0.07	0.13	0.12	0.08	0.08	0.07	0.07
Cr	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	1.23	1.22	1.36	1.34	1.16	1.36	1.11	1.20	1.21	1.15
Mn	0.02	0.03	0.03	0.05	0.02	0.03	0.02	0.02	0.02	0.02
Mg	1.37	1.28	1.13	1.21	1.20	0.74	1.39	1.38	1.27	1.34
Ca	0.38	0.43	0.45	0.39	0.57	0.83	0.46	0.37	0.48	0.47
Mg no.	0.53	0.51	0.45	0.47	0.51	0.35	0.56	0.53	0.51	0.54
Alm.	**41.04**	**41.09**	**45.75**	**45.02**	**39.22**	**45.84**	**37.20**	**40.41**	**40.62**	**38.55**
Spess.	**0.69**	**0.94**	**1.18**	**1.55**	**0.79**	**1.05**	**0.67**	**0.79**	**0.69**	**0.59**
Pyrope	**45.69**	**43.30**	**38.00**	**40.44**	**40.72**	**25.02**	**46.77**	**46.34**	**42.60**	**45.11**
Gross.	**10.54**	**8.08**	**8.73**	**9.68**	**12.59**	**22.01**	**11.27**	**8.43**	**12.67**	**12.12**
Uv.	**0.06**	**0.43**	**0.49**	**0.03**	**0.10**	**0.07**	**0.14**	**0.13**	**0.07**	**0.04**
Andr.	**1.98**	**6.16**	**5.87**	**3.28**	**6.58**	**6.01**	**3.95**	**3.90**	**3.36**	**3.60**

TABLE IV.i (cont)

Opx Ec. profiles (cont)

	218/B/12 core	218/B/1 rim	218/A/9 core(QFK	218/A/18 rim(QFK)	340/A/9 core	340/A/1 rim
SiO2	39.21	38.62	39.10	39.10	39.15	38.48
TiO2	0.15	0.03	0.11	0.06	0.04	0.02
Al2O3	21.61	21.38	21.55	21.59	21.87	21.77
Cr2O3	0.15	0.09	0.04	0.04	0.03	0.00
FeO	21.08	23.37	19.50	15.68	20.09	22.46
MnO	0.41	0.44	0.41	0.40	0.29	0.35
MgO	11.70	9.27	10.87	7.39	10.09	8.48
CaO	5.28	5.97	7.32	14.74	7.95	7.65
Total	99.62	99.22	99.00	99.05	99.55	99.24
Si	2.96	2.97	2.96	2.98	2.96	2.96
Al(iv)	0.04	0.03	0.04	0.02	0.04	0.04
Al(vi)	1.88	1.90	1.89	1.92	1.92	1.93
Ti	0.01	0.00	0.01	0.00	0.00	0.00
Fe'''	0.14	0.12	0.13	0.09	0.11	0.11
Cr	0.01	0.01	0.00	0.00	0.00	0.00
Fe''	1.19	1.38	1.11	0.91	1.16	1.33
Mn	0.03	0.03	0.03	0.03	0.02	0.02
Mg	1.31	1.06	1.23	0.84	1.14	0.97
Ca	0.43	0.49	0.59	1.20	0.64	0.63
Mg no.	0.52	0.43	0.53	0.48	0.50	0.42
Alm.	**40.33**	**46.58**	**37.47**	**30.47**	**39.14**	**45.05**
Spess.	**0.89**	**0.96**	**0.90**	**0.87**	**0.64**	**0.78**
Pyrope	**44.38**	**35.85**	**41.53**	**28.22**	**38.44**	**32.86**
Gross.	**7.27**	**10.32**	**13.62**	**35.72**	**16.12**	**15.79**
Uv.	**0.45**	**0.27**	**0.13**	**0.12**	**0.09**	**0.01**
Andr.	**6.68**	**6.01**	**6.36**	**4.61**	**5.57**	**5.53**

Quartz Ec.

	83/ciii core	83/H rim	83/Ai QF rim
SiO2	38.79	38.30	38.08
TiO2	0.08	0.08	0.06
Al2O3	20.80	21.49	20.59
Cr2O3	0.01	0.03	0.02
FeO	20.79	20.62	24.81
MnO	0.34	0.32	0.08
MgO	5.66	5.74	4.45
CaO	12.78	12.53	11.20
Total	99.28	99.11	99.31
Si	3.01	2.97	2.99
Al(iv)	0.00	0.03	0.01
Al(vi)	1.90	1.93	1.90
Ti	0.00	0.00	0.00
Fe'''	0.08	0.09	0.10
Cr	0.00	0.00	0.00
Fe''	1.27	1.25	1.52
Mn	0.02	0.02	0.01
Mg	0.65	0.66	0.52
Ca	1.06	1.04	0.94
Mg no.	0.34	0.35	0.25
Alm.	**42.19**	**41.99**	**50.93**
Spess.	**0.74**	**0.71**	**0.17**
Pyrope	**21.76**	**22.30**	**17.41**
Gross.	**31.27**	**30.55**	**26.18**
Uv.	**0.03**	**0.08**	**0.07**
Andr.	**4.00**	**4.37**	**5.24**

from Quartz Ec. profiles

	83/A/1 core(QFK	83/A/2 rim(QFK)	83/B/1 core	83/B/H	83/B/L	83/B/R rim	347/A/7 core	347/A/1 rim	351/A/9 core	351/1 rim
SiO2	38.47	38.52	38.10	38.23	38.15	38.19	38.31	38.52	38.27	38.34
TiO2	0.10	0.13	0.11	0.09	0.08	0.07	0.09	0.08	0.07	0.05
Al2O3	21.12	21.21	20.80	20.92	21.16	21.25	21.09	21.23	21.36	21.42
Cr2O3	0.05	0.02	0.01	0.03	0.01	0.01	0.12	0.07	0.01	0.01
FeO	21.13	21.45	24.95	22.56	21.19	22.05	22.15	21.42	21.60	22.28
MnO	0.30	0.50	0.49	0.36	0.34	0.38	0.57	0.49	0.33	0.28
MgO	6.42	6.73	7.18	6.22	5.82	5.24	5.80	5.82	6.28	7.05
CaO	11.88	10.60	7.66	11.10	12.60	12.29	11.44	11.48	11.25	9.56
Total	99.47	99.20	99.34	99.53	99.39	99.49	99.61	99.12	99.20	99.06
Si	2.97	2.98	2.96	2.96	2.95	2.96	2.97	2.99	2.96	2.97
Al(iv)	0.03	0.02	0.04	0.04	0.05	0.04	0.03	0.01	0.04	0.03
Al(vi)	1.89	1.91	1.86	1.87	1.88	1.91	1.89	1.94	1.91	1.92
Ti	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Fe'''	0.13	0.09	0.16	0.16	0.16	0.12	0.12	0.06	0.12	0.11
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Fe''	1.23	1.30	1.46	1.30	1.21	1.31	1.31	1.33	1.28	1.33
Mn	0.02	0.03	0.03	0.02	0.02	0.02	0.04	0.03	0.02	0.02
Mg	0.74	0.77	0.83	0.72	0.67	0.61	0.67	0.67	0.72	0.81
Ca	0.98	0.88	0.64	0.92	1.04	1.02	0.95	0.96	0.93	0.79
Mg no.	0.37	0.37	0.36	0.36	0.36	0.32	0.34	0.34	0.36	0.38
Alm.	**41.42**	**43.44**	**49.26**	**43.87**	**41.10**	**44.28**	**44.23**	**44.53**	**43.30**	**45.12**
Spess.	**0.65**	**1.10**	**1.09**	**0.80**	**0.76**	**0.84**	**1.27**	**1.08**	**0.72**	**0.62**
Pyrope	**24.85**	**26.00**	**28.10**	**24.23**	**22.75**	**20.44**	**22.53**	**22.49**	**24.47**	**27.49**
Gross.	**26.35**	**24.79**	**13.48**	**23.04**	**27.60**	**28.63**	**25.61**	**28.75**	**25.77**	**21.47**
Uv.	**0.15**	**0.07**	**0.04**	**0.09**	**0.04**	**0.03**	**0.36**	**0.22**	**0.03**	**0.03**
Andr.	**6.57**	**4.60**	**8.03**	**7.97**	**7.75**	**5.79**	**6.01**	**2.93**	**5.71**	**5.27**

TABLE IV.i (cont)

	QFK streaks			from profiles				
	350B/6	350B/D	350B/P	350B/A/1	350B/A/1	96/A/4	96/A/9	96/A/10
	core	rim	over.	core	rim	core	rim(2)	rim(1)
SiO2	38.81	38.90	38.74	38.25	38.86	38.43	38.34	37.95
TiO2	0.09	0.06	0.09	0.11	0.06	0.08	0.09	0.06
Al2O3	21.32	21.47	21.66	21.17	21.56	21.38	21.49	21.25
Cr2O3	0.06	0.03	0.02	0.03	0.04	0.03	0.02	0.03
FeO	22.72	18.46	18.87	23.66	18.41	23.52	20.65	23.00
MnO	0.50	0.32	0.41	0.54	0.42	0.45	0.42	0.54
MgO	6.99	6.96	5.51	8.65	6.82	8.46	6.78	5.53
CaO	9.15	13.11	14.90	6.71	13.02	7.07	11.58	10.73
Total	99.70	99.33	100.23	99.19	99.24	99.47	99.42	99.12
Si	2.99	2.98	2.96	2.95	2.98	2.95	2.95	2.96
Al(iv)	0.01	0.02	0.04	0.05	0.02	0.05	0.05	0.04
Al(vi)	1.93	1.92	1.91	1.87	1.93	1.89	1.90	1.91
Ti	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00
Fe'''	0.07	0.09	0.12	0.16	0.08	0.14	0.14	0.12
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	1.40	1.09	1.09	1.36	1.10	1.37	1.19	1.38
Mn	0.03	0.02	0.03	0.04	0.03	0.03	0.03	0.04
Mg	0.80	0.79	0.63	0.99	0.78	0.97	0.78	0.64
Ca	0.76	1.08	1.22	0.55	1.07	0.58	0.95	0.90
Mg no.	0.37	0.42	0.37	0.42	0.41	0.41	0.40	0.32
Alm.	**46.73**	**36.53**	**36.75**	**46.23**	**36.95**	**46.42**	**40.34**	**46.75**
Spess.	**1.10**	**0.69**	**0.89**	**1.20**	**0.91**	**0.99**	**0.94**	**1.21**
Pyrope	**26.86**	**26.65**	**21.19**	**33.75**	**26.19**	**32.85**	**26.36**	**21.72**
Gross.	**21.69**	**31.38**	**35.34**	**10.67**	**31.82**	**12.67**	**25.48**	**24.46**
Uv.	**0.17**	**0.08**	**0.06**	**0.08**	**0.11**	**0.08**	**0.06**	**0.09**
Andr.	**3.45**	**4.66**	**5.78**	**8.07**	**4.01**	**6.99**	**6.82**	**5.77**

	from Grt - amph. profiles				Mylonite profile	
	82/5C	82/8A	84/A/5	84/A/14	Du/A/9	Du4/A/1
	core	rim	core	rim	core	rim
SiO2	38.03	37.96	38.34	38.46	38.22	37.90
TiO2	0.14	0.14	0.09	0.07	0.11	0.07
Al2O3	20.91	20.84	21.11	21.35	20.83	20.89
Cr2O3	0.04	0.02	0.10	0.01	0.08	0.02
FeO	21.80	22.49	21.57	20.65	23.35	25.14
MnO	0.39	0.43	0.46	0.37	0.75	1.25
MgO	5.75	5.74	7.36	6.44	6.62	4.38
CaO	12.11	11.80	9.97	11.95	9.06	9.49
Total	99.20	99.43	99.05	99.35	99.04	99.17
Si	2.95	2.95	2.96	2.96	2.98	2.99
Al(iv)	0.05	0.05	0.04	0.04	0.02	0.01
Al(vi)	1.87	1.85	1.89	1.91	1.89	1.93
Ti	0.01	0.01	0.01	0.00	0.01	0.00
Fe'''	0.16	0.18	0.14	0.12	0.11	0.07
Cr	0.00	0.00	0.01	0.00	0.00	0.00
Fe''	1.26	1.28	1.26	1.21	1.41	1.59
Mn	0.03	0.03	0.03	0.02	0.05	0.08
Mg	0.67	0.66	0.85	0.74	0.77	0.52
Ca	1.01	0.98	0.83	0.99	0.76	0.80
Mg no.	0.35	0.34	0.40	0.38	0.35	0.25
Alm.	**42.55**	**43.33**	**42.47**	**40.88**	**47.18**	**53.13**
Spess.	**0.87**	**0.95**	**1.03**	**0.82**	**1.66**	**2.78**
Pyrope	**22.49**	**22.49**	**28.63**	**24.99**	**25.79**	**17.25**
Gross.	**26.18**	**24.28**	**20.86**	**27.34**	**19.42**	**23.25**
Uv.	**0.13**	**0.07**	**0.29**	**0.04**	**0.24**	**0.06**
Andr.	**7.78**	**8.87**	**6.73**	**5.94**	**5.71**	**3.53**

TABLE IV.ii : Representative analyses - E. Lewisian Cpx

Bimineralic - Eclogite

	E10/IPi core	E5/3 core	E2/9 core	E5/8 rim	E2/6 rim	E6/1 c. sym	E9/4 c. sym	E2/4 sym	E4/2 sym	E3/1 sym
SiO2	53.57	53.37	53.76	53.37	52.40	53.27	52.26	52.10	53.05	53.31
TiO2	0.28	0.31	0.27	0.26	0.34	0.22	0.39	0.42	0.38	0.09
Al2O3	8.18	8.30	10.16	7.91	6.98	4.59	7.91	6.91	3.17	1.26
Cr2O3	0.08	0.14	0.02	0.11	0.12	0.08	0.09	0.03	0.06	0.06
FeO	4.87	4.87	4.28	4.82	4.57	5.31	4.73	4.48	7.11	6.33
MnO	0.06	0.05	0.05	0.07	0.07	0.09	0.09	0.06	0.05	0.34
MgO	10.36	10.79	9.56	10.65	11.97	12.74	11.55	12.15	12.52	13.29
CaO	17.56	17.39	16.30	18.16	20.64	20.42	19.64	21.22	22.26	24.02
Na2O	4.47	4.17	5.05	4.02	2.59	2.30	3.15	2.24	1.88	0.84
Total	99.44	99.40	99.45	99.39	99.68	99.00	99.79	99.62	100.49	99.54
Si	1.94	1.93	1.94	1.94	1.91	1.96	1.89	1.90	1.94	1.98
Al(iv)	0.06	0.07	0.06	0.06	0.09	0.04	0.11	0.10	0.06	0.02
Al(vi)	0.29	0.29	0.37	0.28	0.21	0.16	0.23	0.20	0.08	0.04
Ti	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00
Fe'''	0.07	0.05	0.03	0.05	0.04	0.03	0.07	0.03	0.09	0.04
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	0.08	0.10	0.09	0.09	0.10	0.13	0.07	0.10	0.13	0.16
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Mg	0.56	0.58	0.51	0.58	0.65	0.70	0.62	0.66	0.68	0.74
Ca	0.68	0.68	0.63	0.71	0.81	0.81	0.76	0.83	0.87	0.96
Na	0.31	0.29	0.35	0.28	0.18	0.16	0.22	0.16	0.13	0.06
Jadeite	**28.75**	**28.75**	**35.25**	**27.58**	**18.26**	**15.86**	**22.15**	**15.88**	**7.90**	**3.62**
Aegerine	**2.62**	**0.55**	**0.00**	**0.72**	**0.00**	**0.51**	**0.00**	**0.00**	**5.42**	**2.41**
Tsch.	**5.79**	**6.27**	**5.31**	**5.92**	**7.41**	**3.74**	**9.49**	**7.21**	**5.26**	**1.80**
Heden.	**7.88**	**9.80**	**9.60**	**9.62**	**9.74**	**13.48**	**7.48**	**10.50**	**13.00**	**17.05**
Diopside	**54.96**	**54.64**	**49.83**	**56.16**	**64.58**	**66.41**	**60.88**	**66.42**	**68.42**	**75.12**

E9 profile C. Gnt Quartz Ec.

	353/3 core	E9/C/6 core	E9/C/1 rim	C4/2		83/16 core	83/13 rim	83/11 sym	347/1 core	347/2 rim
SiO2	53.79	53.94	53.59	53.77		51.88	50.59	51.18	53.68	52.68
TiO2	0.26	0.27	0.24	0.14		0.35	0.48	0.41	0.23	0.24
Al2O3	8.67	9.79	9.21	3.04		9.43	8.35	3.83	11.80	6.06
Cr2O3	0.07	0.06	0.11	0.05		0.02	0.05	0.08	0.07	0.00
FeO	4.83	4.38	4.47	5.38		6.32	6.75	7.71	5.21	6.06
MnO	0.04	0.07	0.10	0.17		0.02	0.02	0.07	0.02	0.06
MgO	10.27	10.15	10.45	13.94		9.47	10.30	11.70	8.30	11.60
CaO	16.87	16.66	17.60	21.46		17.58	19.79	23.41	14.83	20.80
Na2O	4.86	4.85	4.35	1.83		4.02	2.68	0.67	5.57	2.51
Total	99.67	100.16	100.11	99.79		99.08	99.00	99.10	99.72	100.00
Si	1.94	1.93	1.92	1.96		1.90	1.87	1.92	1.93	1.92
Al(iv)	0.06	0.07	0.08	0.04		0.10	0.13	0.08	0.07	0.08
Al(vi)	0.30	0.34	0.31	0.10		0.31	0.23	0.09	0.43	0.18
Ti	0.01	0.01	0.01	0.00		0.01	0.01	0.01	0.01	0.01
Fe'''	0.08	0.05	0.05	0.06		0.06	0.06	0.01	0.01	0.06
Cr	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00
Fe''	0.06	0.08	0.09	0.10		0.13	0.15	0.24	0.14	0.13
Mn	0.00	0.00	0.00	0.01		0.00	0.00	0.00	0.00	0.00
Mg	0.55	0.54	0.56	0.76		0.52	0.57	0.66	0.44	0.63
Ca	0.65	0.64	0.68	0.84		0.69	0.78	0.94	0.57	0.81
Na	0.34	0.34	0.30	0.13		0.29	0.19	0.05	0.39	0.18
Jadeite	**30.39**	**33.62**	**30.25**	**9.58**		**28.53**	**19.21**	**4.91**	**38.80**	**17.76**
Aegerine	**3.54**	**0.00**	**0.00**	**3.41**		**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Tsch.	**6.07**	**6.38**	**6.65**	**3.34**		**8.72**	**10.33**	**4.76**	**4.58**	**7.00**
Heden.	**6.30**	**8.49**	**8.96**	**10.94**		**13.16**	**14.77**	**23.91**	**14.42**	**13.03**
Diopside	**53.70**	**51.51**	**54.14**	**72.74**		**49.60**	**55.69**	**66.42**	**42.20**	**62.22**

TABLE IV.ii (cont.)

	Biot. Ec.	QFK	Orthopyroxene - eclogite				
	512/6	350b/A	511/1	511/5	223/A	223/12	224/6
		gnt incl	core	poly	core	rim	sym
SiO2	54.44	52.02	53.36	53.58	54.80	54.47	53.69
TiO2	0.28	0.29	0.16	0.12	0.19	0.23	0.10
Al2O3	7.58	11.73	4.18	3.11	6.91	11.12	2.77
Cr2O3	0.01	0.01	0.22	0.31	0.05	0.02	0.01
FeO	8.62	4.92	4.28	4.04	4.77	3.90	4.04
MnO	0.05	0.04	0.06	0.04	0.05	0.04	0.05
MgO	8.85	8.87	13.77	15.09	11.97	9.39	14.49
CaO	13.53	16.56	20.90	21.65	16.13	14.70	22.50
Na2O	6.29	4.84	2.23	1.65	4.36	5.37	1.42
Total	99.65	99.29	99.16	99.59	99.23	99.23	99.08
Si	1.97	1.88	1.95	1.95	1.98	1.96	1.97
Al(iv)	0.03	0.12	0.05	0.05	0.02	0.04	0.03
Al(vi)	0.29	0.38	0.13	0.08	0.27	0.43	0.09
Ti	0.01	0.01	0.00	0.00	0.01	0.01	0.00
Fe'''	0.17	0.06	0.06	0.07	0.04	0.00	0.03
Cr	0.00	0.00	0.01	0.01	0.00	0.00	0.00
Fe''	0.09	0.09	0.07	0.06	0.10	0.12	0.09
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.48	0.48	0.75	0.82	0.64	0.50	0.79
Ca	0.52	0.64	0.82	0.84	0.62	0.57	0.89
Na	0.44	0.34	0.16	0.12	0.31	0.37	0.10
Jadeite	**28.97**	**33.95**	**13.01**	**8.43**	**27.39**	**37.46**	**9.17**
Aegerine	**15.07**	**0.00**	**2.82**	**3.19**	**3.17**	**0.00**	**0.96**
Tsch.	**2.94**	**9.32**	**4.77**	**4.78**	**1.81**	**2.38**	**2.68**
Heden.	**9.37**	**9.02**	**6.96**	**5.80**	**10.45**	**11.86**	**9.35**
Diopside	**43.66**	**47.71**	**72.44**	**77.80**	**57.18**	**48.31**	**77.84**

	Opx Ec. (cont)				223 profile				
	337/7	337/1	338/3	338/4	223/A/1	223/A/2	223/A/3	223/A/4	223/A/7
	core	rim	core	poly					
SiO2	53.33	53.69	53.11	53.11	54.86	54.69	54.70	54.55	54.29
TiO2	0.17	0.09	0.22	0.16	0.24	0.24	0.22	0.22	0.21
Al2O3	3.06	2.71	4.53	4.46	14.52	11.42	9.29	7.33	4.89
Cr2O3	0.09	0.08	0.04	0.02	0.10	0.06	0.07	0.03	0.06
FeO	6.40	5.56	5.64	5.75	3.16	3.88	4.38	4.87	4.63
MnO	0.06	0.05	0.03	0.06	0.03	0.04	0.04	0.03	0.01
MgO	13.20	13.69	12.50	12.54	7.24	8.74	9.72	10.75	12.38
CaO	20.86	21.54	20.67	20.52	11.39	13.42	14.82	16.44	18.83
Na2O	2.14	1.88	2.44	2.53	8.74	7.46	6.44	5.43	3.92
Total	99.31	99.28	99.19	99.15	100.28	99.94	99.67	99.65	99.22
Si	1.96	1.97	1.95	1.95	1.91	1.93	1.95	1.95	1.97
Al(iv)	0.04	0.03	0.05	0.05	0.09	0.07	0.05	0.05	0.03
Al(vi)	0.09	0.09	0.15	0.14	0.51	0.40	0.34	0.26	0.18
Ti	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01
Fe'''	0.08	0.06	0.06	0.08	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	0.11	0.11	0.11	0.10	0.09	0.11	0.13	0.15	0.14
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.72	0.75	0.68	0.69	0.38	0.46	0.52	0.57	0.67
Ca	0.82	0.85	0.81	0.81	0.43	0.51	0.57	0.63	0.73
Na	0.15	0.13	0.17	0.18	0.59	0.51	0.44	0.38	0.28
Jadeite	**9.50**	**9.06**	**14.67**	**14.33**	**50.70**	**40.16**	**33.63**	**26.40**	**17.66**
Aegerine	**5.79**	**4.36**	**2.70**	**3.69**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Tsch.	**3.56**	**2.55**	**4.64**	**4.77**	**4.92**	**4.05**	**3.06**	**2.61**	**1.99**
Heden.	**11.49**	**10.95**	**11.14**	**10.07**	**9.29**	**11.53**	**13.14**	**14.69**	**14.08**
Diopside	**69.66**	**73.09**	**66.85**	**67.14**	**35.09**	**44.26**	**50.18**	**56.29**	**66.26**

TABLE IV.iii : Representative analyses - E. Lewisian Am

Bimineralic eclogite

	E5/3 primary	E2/10 primary	E9/3 primary	E10/i primary	E2/3 gnt alt	E3/10 gnt alt	E5/2 gnt alt	E9/1 gnt alt	353/5 px alt	E1/2 px alt
SiO2	42.34	42.57	41.59	43.37	41.58	53.51	41.04	39.76	46.45	45.32
TiO2	0.57	1.40	0.82	0.22	1.41	0.23	0.19	0.22	0.40	0.29
Al2O3	15.23	13.62	15.17	14.64	16.24	2.50	16.06	16.95	9.13	10.51
Cr2O3	0.09	0.08	0.07	0.07	0.06	0.04	0.14	0.08	0.12	0.04
FeO	11.27	10.13	10.69	10.78	9.21	12.16	12.67	13.20	11.84	14.11
MnO	0.09	0.08	0.12	0.12	0.10	0.22	0.26	0.27	0.06	0.31
MgO	12.85	13.20	12.50	12.64	12.75	14.91	11.39	10.00	14.05	12.03
CaO	10.95	11.77	10.89	11.87	11.91	12.65	11.32	11.45	11.89	12.05
Na2O	3.38	2.20	2.90	2.88	2.37	0.38	3.17	2.71	1.41	2.27
K2O	0.39	1.27	1.52	0.14	0.91	0.11	0.37	1.16	0.47	0.37
Total	**97.14**	**96.33**	**96.26**	**96.71**	**96.54**	**96.71**	**96.62**	**95.79**	**95.82**	**97.31**
Si	6.15	6.29	6.16	6.35	6.10	7.79	6.06	6.00	6.82	6.70
Al (iv)	1.85	1.71	1.84	1.65	1.90	0.21	1.94	2.00	1.18	1.30
Al (vi)	0.76	0.66	0.80	0.88	0.91	0.22	0.86	1.02	0.40	0.53
Ti	0.06	0.16	0.09	0.02	0.16	0.03	0.02	0.02	0.04	0.03
Fe'''	0.52	0.13	0.28	0.16	0.09	0.00	0.46	0.21	0.44	0.17
Cr	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01
Fe	0.85	1.12	1.04	1.16	1.04	1.48	1.10	1.45	1.01	1.58
Mn	0.01	0.01	0.01	0.02	0.01	0.03	0.03	0.03	0.01	0.04
Mg	2.78	2.91	2.76	2.76	2.79	3.24	2.51	2.25	3.08	2.65
Ca	1.72	1.87	1.74	1.87	1.88	1.97	1.81	1.86	1.89	1.92
Na	0.96	0.63	0.84	0.82	0.68	0.11	0.92	0.80	0.41	0.65
K	0.07	0.24	0.29	0.03	0.17	0.02	0.07	0.22	0.09	0.07

	E1/4 px alt	E3/3 px alt	E2/7 vein	E9/2 vein	E10/iv vein	E6/A/A vein	353/1 vein	353/9 vein
SiO2	43.77	48.46	44.04	41.64	41.45	38.84	48.86	48.60
TiO2	0.81	0.45	0.31	0.18	0.66	0.27	0.61	0.75
Al2O3	11.85	7.30	11.65	13.73	14.48	19.93	7.78	7.27
Cr2O3	0.03	0.04	0.03	0.22	0.08	0.06	0.00	0.12
FeO	13.91	10.49	13.33	12.91	15.21	11.00	9.88	12.06
MnO	0.25	0.24	0.32	0.28	0.27	0.08	0.15	0.18
MgO	11.48	14.49	12.34	11.72	10.01	11.45	16.08	14.49
CaO	11.97	12.37	12.32	11.70	11.23	10.87	12.09	11.56
Na2O	2.52	1.54	1.90	2.69	3.38	2.87	1.56	1.47
K2O	0.45	0.22	0.23	0.90	0.39	0.38	0.27	0.24
Total	**97.03**	**95.59**	**96.47**	**95.96**	**97.15**	**95.75**	**97.28**	**96.75**
Si	6.52	7.16	6.52	6.25	6.20	5.68	6.99	7.05
Al (iv)	1.48	0.84	1.48	1.75	1.80	2.32	1.01	0.95
Al (vi)	0.60	0.43	0.55	0.68	0.75	1.11	0.30	0.29
Ti	0.09	0.05	0.03	0.02	0.07	0.03	0.07	0.08
Fe'''	0.08	0.00	0.37	0.30	0.24	0.86	0.39	0.44
Cr	0.00	0.01	0.00	0.03	0.01	0.01	0.00	0.01
Fe	1.66	1.30	1.28	1.32	1.66	0.49	0.80	1.02
Mn	0.03	0.03	0.04	0.03	0.03	0.01	0.02	0.02
Mg	2.55	3.19	2.72	2.62	2.23	2.49	3.43	3.13
Ca	1.91	1.95	1.97	1.89	1.81	1.74	1.87	1.81
Na	0.73	0.44	0.55	0.79	0.99	0.83	0.44	0.42
K	0.09	0.04	0.04	0.17	0.07	0.07	0.05	0.04

TABLE IV.iii (cont.)

Quartz - eclogite

	353/15	353/14	353/5	353/2	353/1	353/3	83/3	83/I	83/F	83/A
SiO2	42.21	39.47	46.45	41.59	48.86	47.32	36.51	46.76	39.87	36.62
TiO2	1.00	0.55	0.40	1.14	0.61	0.55	0.33	0.27	0.07	0.81
Al2O3	14.91	17.71	9.13	14.01	7.78	9.02	19.77	8.59	16.44	18.71
Cr2O3	0.07	0.06	0.12	0.07	0.00	0.05	0.03	0.00	0.01	0.01
FeO	10.45	12.14	11.84	12.54	9.88	11.13	16.17	14.54	18.08	17.88
MnO	0.05	0.06	0.06	0.12	0.15	0.14	0.09	0.06	0.13	0.08
MgO	13.14	11.33	14.05	11.80	16.08	14.70	7.42	12.62	7.52	6.64
CaO	10.34	11.61	11.89	11.19	12.09	12.05	11.59	12.08	11.58	11.83
Na2O	2.64	2.23	1.41	2.18	1.56	1.63	1.75	1.17	1.71	1.65
K2O	2.18	1.56	0.47	2.10	0.27	0.37	1.90	0.54	0.86	1.59
Total	**96.99**	**96.71**	**95.82**	**96.74**	**97.28**	**96.95**	**95.54**	**96.62**	**96.28**	**95.81**
Si	6.17	5.84	6.82	6.20	6.99	6.85	5.60	6.90	6.04	5.65
Al (iv)	1.83	2.16	1.18	1.80	1.01	1.15	2.40	1.10	1.96	2.35
Al (vi)	0.74	0.93	0.40	0.66	0.30	0.40	1.18	0.39	0.98	1.06
Ti	0.11	0.06	0.04	0.13	0.07	0.06	0.04	0.03	0.01	0.09
Fe'''	0.48	0.50	0.44	0.27	0.39	0.36	0.45	0.40	0.53	0.38
Cr	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00
Fe	0.80	1.00	1.01	1.29	0.80	0.99	1.62	1.40	1.76	1.92
Mn	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.02	0.01
Mg	2.86	2.50	3.08	2.62	3.43	3.17	1.70	2.78	1.70	1.53
Ca	1.64	1.86	1.89	1.80	1.87	1.88	1.92	1.93	1.90	1.97
Na	0.76	0.65	0.41	0.63	0.44	0.46	0.52	0.34	0.51	0.50
K	0.41	0.30	0.09	0.40	0.05	0.07	0.38	0.10	0.17	0.32

Biotite eclogite / Amphib.

	Biotite eclogite 512/3	512/4	512/A	Amphib. 82/6	82/7
SiO2	45.58	55.44	55.52	40.92	37.59
TiO2	1.57	0.04	0.03	0.49	0.09
Al2O3	9.02	0.19	0.10	15.73	19.70
Cr2O3	0.04	0.00	0.00	0.01	0.01
FeO	12.83	20.06	19.41	17.77	18.94
MnO	0.05	0.13	0.11	0.24	0.27
MgO	13.60	20.49	21.11	7.52	5.37
CaO	10.51	0.77	0.33	11.78	11.80
Na2O	2.50	0.04	0.03	1.42	1.57
K2O	0.65	0.01	0.02	0.39	0.66
Total	**96.34**	**97.17**	**96.66**	**96.27**	**96.00**
Si	6.70	8.06	8.05	6.18	5.75
Al (iv)	1.30	0.00	0.00	1.82	2.25
Al (vi)	0.26	0.03	0.02	0.98	1.31
Ti	0.17	0.00	0.00	0.06	0.01
Fe'''	0.55	0.00	0.00	0.44	0.46
Cr	0.01	0.00	0.00	0.00	0.00
Fe	1.03	2.44	2.35	1.81	1.96
Mn	0.01	0.02	0.01	0.03	0.03
Mg	2.98	4.44	4.56	1.69	1.23
Ca	1.67	0.12	0.05	1.92	1.95
Na	0.72	0.01	0.01	0.42	0.47
K	0.12	0.00	0.00	0.08	0.13

TABLE IV.iii (cont.)

Orthopyroxene eclogite

	511/2	511/1	223/1	224/4A	224/6A	342/H	224/2	217/vi	337/A	217/H
SiO2	54.28	47.03	54.89	53.62	54.53	40.38	51.81	45.66	45.79	44.35
TiO2	0.10	0.52	0.14	0.27	0.09	0.09	0.44	0.77	1.46	0.70
Al2O3	2.73	9.86	2.00	6.51	1.65	21.57	4.53	10.98	11.31	12.19
Cr2O3	0.10	0.34	0.01	0.04	0.01	0.12	0.02	0.10	0.27	0.02
FeO	7.10	9.39	4.19	8.89	13.29	10.18	10.52	10.05	8.60	10.14
MnO	0.12	0.23	0.04	0.13	0.25	0.13	0.28	0.04	0.04	0.08
MgO	18.83	14.99	21.75	14.67	19.69	10.26	16.52	13.93	15.19	14.19
CaO	13.17	11.94	12.33	11.71	6.67	12.31	11.70	11.32	11.18	12.83
Na2O	0.35	1.62	0.55	0.84	0.19	1.73	0.56	2.29	2.82	1.94
K2O	0.04	0.51	0.25	0.04	0.03	0.33	0.04	0.64	0.03	1.22
Total	**96.82**	**96.44**	**96.14**	**96.72**	**96.39**	**97.10**	**96.41**	**95.76**	**96.69**	**97.65**
Si	7.69	6.81	7.65	7.67	7.29	5.84	7.39	6.71	6.59	6.48
Al (iv)	0.31	1.19	0.35	0.33	0.71	2.16	0.61	1.29	1.41	1.52
Al (vi)	0.15	0.50	-0.02	0.76	-0.45	1.52	0.15	0.61	0.51	0.58
Ti	0.01	0.06	0.02	0.03	0.01	0.01	0.05	0.08	0.16	0.08
Fe'''	0.03	0.28	0.47	-0.32	3.17	0.25	0.63	0.16	0.31	-0.01
Cr	0.01	0.04	0.00	0.00	0.00	0.01	0.00	0.01	0.03	0.00
Fe	0.81	0.86	0.02	1.38	-1.69	0.98	0.63	1.07	0.72	1.25
Mn	0.01	0.03	0.00	0.02	0.03	0.02	0.03	0.00	0.00	0.01
Mg	3.98	3.24	4.52	3.13	3.92	2.21	3.51	3.05	3.26	3.09
Ca	2.00	1.87	1.86	1.78	1.03	1.92	1.81	1.79	1.74	2.01
Na	0.10	0.46	0.15	0.23	0.05	0.49	0.16	0.65	0.79	0.55
K	0.01	0.10	0.05	0.01	0.00	0.06	0.01	0.12	0.00	0.23

	217/2	337/4	337/1	217/A	217/L
SiO2	38.26	38.23	46.35	39.28	52.84
TiO2	0.07	0.08	0.43	0.19	0.28
Al2O3	20.98	17.88	9.55	18.79	3.45
Cr2O3	0.05	0.14	0.18	0.02	0.00
FeO	11.95	14.71	13.61	12.09	9.26
MnO	0.09	0.13	0.20	0.12	0.15
MgO	9.75	9.83	12.87	10.44	17.31
CaO	11.60	11.70	11.42	11.88	12.52
Na2O	2.63	2.93	1.89	2.06	0.19
K2O	0.34	0.44	0.16	1.39	0.06
Total	**95.70**	**96.07**	**96.66**	**96.27**	**96.05**
Si	5.67	5.74	6.79	5.84	7.57
Al (iv)	2.33	2.26	1.21	2.16	0.43
Al (vi)	1.34	0.91	0.43	1.14	0.15
Ti	0.01	0.01	0.05	0.02	0.03
Fe'''	0.47	0.61	0.52	0.33	0.32
Cr	0.01	0.02	0.02	0.00	0.00
Fe	1.01	1.23	1.15	1.18	0.79
Mn	0.01	0.02	0.02	0.02	0.02
Mg	2.15	2.20	2.81	2.32	3.69
Ca	1.86	1.91	1.81	1.91	1.93
Na	0.76	0.86	0.54	0.60	0.05
K	0.07	0.08	0.03	0.27	0.01

TABLE IV.iv : Representative analyses - E. Lew. sed. Grt

Marble nodules

	260r3/365	260/9	261/1	261/2	261/5	263/2	312/4	312/6	313/1	72/2
	core	rim	core	rim	rim					
SiO2	36.71	37.20	37.20	37.13	38.12	38.89	38.71	39.16	39.25	38.37
TiO2	0.06	0.05	0.04	0.06	0.06	0.19	0.09	0.36	0.23	0.09
Al2O3	20.15	20.36	19.81	19.87	20.50	21.36	19.79	19.77	20.97	21.34
Cr2O3	0.03	0.07	0.06	0.04	0.02	0.03	0.04	0.05	0.03	0.00
FeO	34.47	33.48	32.81	32.57	28.81	13.63	18.72	12.51	9.06	13.49
MnO	0.63	0.85	0.66	3.34	1.32	0.81	1.36	1.03	0.98	1.43
MgO	4.03	3.57	4.58	3.93	7.00	4.30	6.07	5.07	5.10	1.94
CaO	3.29	4.14	4.10	2.55	4.07	19.81	14.28	21.57	23.65	22.53
Total	**99.39**	**99.76**	**99.30**	**99.54**	**99.96**	**99.05**	**99.10**	**99.54**	**99.28**	**99.18**
Si	2.95	2.98	2.98	2.99	2.98	2.99	3.00	2.99	2.97	2.98
Al(iv)	0.05	0.02	0.02	0.01	0.02	0.01	0.00	0.01	0.03	0.02
Al(vi)	1.86	1.90	1.85	1.87	1.86	1.93	1.80	1.77	1.85	1.93
Ti	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.01	0.00
Fe'''	0.18	0.11	0.17	0.13	0.15	0.06	0.19	0.20	0.15	0.08
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	2.14	2.14	2.03	2.06	1.73	0.82	1.03	0.60	0.42	0.79
Mn	0.04	0.06	0.04	0.23	0.09	0.05	0.09	0.07	0.06	0.09
Mg	0.48	0.43	0.55	0.47	0.81	0.49	0.70	0.58	0.58	0.22
Ca	0.28	0.36	0.35	0.22	0.34	1.63	1.18	1.76	1.92	1.87
Mg No.	18.41	16.62	21.22	18.60	32.04	37.64	40.57	49.00	57.57	22.08
Alm.	**72.57**	**71.80**	**68.27**	**69.20**	**58.18**	**27.28**	**34.18**	**19.97**	**14.22**	**26.51**
Spess.	**1.45**	**1.94**	**1.51**	**7.63**	**2.93**	**1.75**	**2.98**	**2.21**	**2.11**	**3.15**
Pyrope	**16.37**	**14.31**	**18.39**	**15.81**	**27.43**	**16.47**	**23.34**	**19.18**	**19.30**	**7.51**
Gross.	**0.70**	**6.33**	**3.27**	**0.69**	**3.69**	**50.90**	**29.76**	**47.51**	**56.20**	**58.39**
Uv.	**0.08**	**0.21**	**0.18**	**0.11**	**0.06**	**0.09**	**0.13**	**0.15**	**0.08**	**0.00**
Andr.	**8.82**	**5.41**	**8.37**	**6.55**	**7.71**	**3.51**	**9.62**	**10.97**	**8.08**	**4.44**

Eulysite

	228/1	94/4	95/1	95/2	95/3	95/4
SiO2	36.10	35.87	36.52	36.53	36.65	36.62
TiO2	0.08	0.05	0.19	0.15	0.34	0.26
Al2O3	19.36	17.19	19.37	19.40	19.18	18.66
Cr2O3	0.00	0.00	0.02	0.00	0.01	0.00
FeO	27.37	13.75	24.09	24.32	19.82	19.20
MnO	12.09	25.86	13.16	13.29	17.04	14.66
MgO	0.80	0.32	0.45	0.46	0.39	0.33
CaO	3.58	5.43	5.53	5.32	6.28	9.41
Total	**99.38**	**98.51**	**99.33**	**99.47**	**99.76**	**99.19**
Si	2.97	2.99	3.00	3.00	2.99	2.99
Al(iv)	0.03	0.01	0.00	0.00	0.01	0.01
Al(vi)	1.85	1.68	1.88	1.87	1.84	1.79
Ti	0.01	0.00	0.01	0.01	0.02	0.02
Fe'''	0.16	0.32	0.10	0.11	0.12	0.19
Cr	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	1.72	0.64	1.55	1.56	1.23	1.12
Mn	0.84	1.83	0.92	0.92	1.18	1.01
Mg	0.10	0.04	0.05	0.06	0.05	0.04
Ca	0.32	0.49	0.49	0.47	0.55	0.82
Mg No.	5.40	5.93	3.42	3.45	3.67	3.42
Alm.	**57.78**	**21.30**	**51.60**	**51.87**	**40.91**	**37.40**
Spess.	**28.31**	**61.12**	**30.42**	**30.72**	**39.24**	**33.82**
Pyrope	**3.30**	**1.34**	**1.83**	**1.85**	**1.56**	**1.32**
Gross.	**2.24**	**0.03**	**10.42**	**9.58**	**10.93**	**17.15**
Uv.	**0.00**	**0.00**	**0.06**	**0.00**	**0.05**	**0.00**
Andr.	**8.37**	**16.21**	**5.68**	**5.98**	**7.32**	**10.31**

TABLE IV.iv (cont.)

Metapelites

	315/1 core	315/3 rim	316/1 core	316/4 rim	317/2 core	317/5 rim	318/1 rim	10/1. core	10/2. rim	7/1. core
SiO2	37.59	37.26	38.54	38.28	38.78	37.92	37.07	38.96	38.56	38.55
TiO2	0.04	0.06	0.04	0.06	0.04	0.05	0.08	0.03	0.05	0.02
Al2O3	21.08	20.87	21.17	21.28	21.97	21.46	20.52	21.99	21.68	21.54
Cr2O3	0.04	0.06	0.16	0.07	0.06	0.04	0.08	0.05	0.03	0.08
FeO	31.12	32.09	27.86	29.06	26.48	29.13	34.26	24.13	26.32	25.21
MnO	0.34	0.37	0.41	0.47	0.42	0.63	0.42	0.22	0.30	0.20
MgO	6.93	5.90	8.00	5.92	9.47	5.96	4.81	10.19	8.20	10.11
CaO	2.10	2.66	3.40	5.14	3.10	4.90	2.07	4.25	4.39	3.59
Total	**99.28**	**99.33**	**99.61**	**100.33**	**100.46**	**100.14**	**99.36**	**99.85**	**99.54**	**99.29**
Si	2.96	2.95	3.00	2.99	2.96	2.96	2.97	2.96	2.98	2.96
Al(iv)	0.04	0.05	0.00	0.01	0.04	0.04	0.03	0.04	0.02	0.04
Al(vi)	1.92	1.91	1.94	1.94	1.93	1.94	1.91	1.94	1.96	1.91
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe'''	0.11	0.13	0.05	0.06	0.10	0.09	0.11	0.09	0.05	0.12
Cr	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	1.95	2.00	1.76	1.83	1.58	1.81	2.19	1.44	1.66	1.49
Mn	0.02	0.02	0.03	0.03	0.03	0.04	0.03	0.01	0.02	0.01
Mg	0.81	0.70	0.93	0.69	1.08	0.69	0.57	1.16	0.95	1.16
Ca	0.18	0.23	0.28	0.43	0.25	0.41	0.18	0.35	0.36	0.29
Mg No.	29.50	25.85	34.50	27.29	40.46	27.70	20.80	44.44	36.35	43.63
Alm.	**65.73**	**67.84**	**58.71**	**61.48**	**53.86**	**61.26**	**73.70**	**48.80**	**55.47**	**50.50**
Spess.	**0.76**	**0.84**	**0.91**	**1.04**	**0.93**	**1.40**	**0.95**	**0.47**	**0.65**	**0.44**
Pyrope	**27.51**	**23.65**	**30.93**	**23.07**	**36.60**	**23.47**	**19.35**	**39.03**	**31.69**	**39.10**
Gross.	**0.60**	**1.11**	**6.18**	**11.00**	**3.22**	**9.15**	**0.14**	**7.01**	**9.62**	**3.62**
Uv.	**0.12**	**0.17**	**0.49**	**0.20**	**0.18**	**0.12**	**0.24**	**0.13**	**0.09**	**0.24**
Andr.	**5.29**	**6.39**	**2.78**	**3.21**	**5.21**	**4.60**	**5.62**	**4.55**	**2.48**	**6.10**

	7/2. rim	8./1 core	8./2 rim	271/4	98/1 core	98/10 rim
SiO2	37.19	37.86	37.98	37.37	38.62	37.59
TiO2	0.01	0.02	0.01	0.04	0.07	0.04
Al2O3	20.95	21.37	21.43	20.95	21.48	20.97
Cr2O3	0.07	0.04	0.03	0.00	0.10	0.03
FeO	32.13	30.86	30.17	32.82	26.74	30.52
MnO	0.72	0.67	0.45	0.29	0.54	0.94
MgO	4.25	4.73	5.72	4.97	9.33	4.47
CaO	4.47	5.14	4.35	3.83	3.14	5.42
Total	**99.80**	**100.71**	**100.17**	**100.27**	**100.05**	**100.02**
Si	2.96	2.97	2.97	2.95	2.96	2.97
Al(iv)	0.04	0.03	0.03	0.05	0.04	0.03
Al(vi)	1.92	1.94	1.95	1.90	1.91	1.92
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Fe'''	0.11	0.09	0.07	0.14	0.11	0.10
Cr	0.00	0.00	0.00	0.00	0.01	0.00
Fe''	2.02	1.94	1.91	2.02	1.60	1.92
Mn	0.05	0.04	0.03	0.02	0.04	0.06
Mg	0.50	0.55	0.67	0.59	1.07	0.53
Ca	0.38	0.43	0.36	0.32	0.26	0.46
Mg No.	19.92	22.19	25.91	22.43	39.98	21.52
Alm.	**68.46**	**65.32**	**64.24**	**68.55**	**54.08**	**64.67**
Spess.	**1.64**	**1.51**	**1.00**	**0.65**	**1.19**	**2.12**
Pyrope	**17.03**	**18.63**	**22.47**	**19.82**	**36.01**	**17.74**
Gross.	**7.03**	**10.13**	**8.80**	**3.88**	**2.62**	**10.37**
Uv.	**0.21**	**0.11**	**0.10**	**0.00**	**0.30**	**0.10**
Andr.	**5.63**	**4.30**	**3.38**	**7.09**	**5.80**	**5.00**

TABLE IV.v : representative analyses - E. L. sed - Cpx

Marble Nodules

	260/NV3	260/5	261/1	261/2	261/10	261/C	263/A	263/B	263/C	313/1
	vein rim	core	core	rim			sphene	no sphene	ap incl.	core
SiO2	53.25	54.70	53.26	54.34	54.78	54.04	51.12	51.62	51.73	52.10
TiO2	0.18	0.26	0.29	0.13	0.08	0.12	0.73	0.71	0.49	0.21
Al2O3	3.87	9.63	7.86	4.07	0.68	1.19	6.88	6.66	8.26	4.27
Cr2O3	0.10	0.07	0.05	0.06	0.03	0.01	0.04	0.07	0.01	0.00
FeO	12.78	12.37	10.96	9.79	2.09	3.83	6.85	4.70	4.70	3.28
MnO	0.09	0.07	0.27	0.23	0.06	0.08	0.08	0.05	0.07	0.09
MgO	8.37	4.84	7.00	10.14	17.32	15.64	10.35	12.04	10.97	14.71
CaO	16.79	9.24	13.49	18.70	25.32	24.75	20.76	21.90	20.63	24.13
Na2O	3.79	8.25	6.30	3.36	0.26	0.60	2.68	2.15	2.96	0.85
Total	**99.23**	**99.42**	**99.48**	**100.81**	**100.62**	**100.28**	**99.50**	**99.89**	**99.84**	**99.65**
Si	2.00	1.99	1.95	1.99	1.98	1.97	1.88	1.88	1.88	1.90
Al(iv)	0.00	0.01	0.05	0.01	0.02	0.03	0.12	0.12	0.12	0.10
Al(vi)	0.17	0.41	0.29	0.16	0.00	0.02	0.18	0.17	0.23	0.09
Ti	0.01	0.01	0.01	0.00	0.00	0.00	0.02	0.02	0.01	0.01
Fe'''	0.10	0.17	0.19	0.08	0.03	0.05	0.08	0.06	0.07	0.06
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	0.30	0.21	0.14	0.22	0.03	0.07	0.13	0.09	0.08	0.04
Mn	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.47	0.26	0.38	0.55	0.93	0.85	0.57	0.66	0.59	0.80
Ca	0.67	0.36	0.53	0.73	0.98	0.97	0.82	0.86	0.80	0.94
Na	0.28	0.58	0.45	0.24	0.02	0.04	0.19	0.15	0.21	0.06
Jadeite	**16.87**	**40.57**	**28.85**	**16.34**	**0.45**	**1.90**	**18.40**	**15.19**	**20.83**	**6.02**
Aeg.	**10.72**	**17.68**	**15.84**	**7.48**	**1.34**	**2.33**	**0.74**	**0.00**	**0.00**	**0.00**
Tsch.	**0.02**	**0.44**	**4.67**	**1.06**	**2.33**	**3.09**	**10.51**	**10.64**	**11.31**	**9.51**
Heden.	**30.64**	**21.02**	**15.22**	**22.77**	**3.20**	**6.97**	**13.29**	**8.81**	**7.84**	**4.23**
Diop.	**41.74**	**20.28**	**35.42**	**52.35**	**92.69**	**85.71**	**57.08**	**65.36**	**60.02**	**80.24**

Marble Nodules (cont.)

	313/2	312/2	312/3	312/6	312/10	72/3	120/1	120/2	203/1	204/3
	rim	core	rim		large core		sym	core		
SiO2	47.40	50.43	50.93	49.89	51.20	52.47	52.30	52.92	54.42	54.20
TiO2	1.34	0.50	0.58	0.43	0.45	0.18	0.34	0.30	0.06	0.20
Al2O3	8.78	3.91	3.98	5.84	4.10	3.20	5.24	9.36	0.67	2.18
Cr2O3	0.01	0.08	0.04	0.00	0.02	0.01	0.01	0.16	0.01	0.00
FeO	3.71	4.01	4.30	4.68	4.46	6.71	3.42	2.89	1.35	1.99
MnO	0.08	0.08	0.08	0.06	0.07	0.13	0.13	0.08	0.12	0.25
MgO	12.84	14.90	14.97	14.01	14.63	12.70	13.51	10.87	17.50	15.72
CaO	24.70	24.68	24.84	24.67	24.70	22.87	22.43	18.46	25.77	24.80
Na2O	0.46	0.47	0.46	0.51	0.50	1.12	1.81	4.08	0.07	0.63
Total	**99.32**	**99.07**	**100.17**	**100.09**	**100.13**	**99.41**	**99.20**	**99.13**	**99.98**	**99.99**
Si	1.75	1.86	1.86	1.82	1.87	1.95	1.91	1.91	1.97	1.97
Al(iv)	0.25	0.14	0.14	0.18	0.13	0.05	0.09	0.09	0.03	0.03
Al(vi)	0.13	0.03	0.03	0.08	0.05	0.09	0.14	0.31	0.00	0.06
Ti	0.04	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.01
Fe'''	0.08	0.11	0.11	0.11	0.09	0.03	0.06	0.04	0.03	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	0.03	0.01	0.02	0.03	0.05	0.17	0.04	0.05	0.01	0.06
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Mg	0.71	0.82	0.81	0.76	0.80	0.70	0.74	0.59	0.95	0.85
Ca	0.98	0.98	0.97	0.97	0.97	0.91	0.88	0.71	1.00	0.97
Na	0.03	0.03	0.03	0.04	0.04	0.08	0.13	0.29	0.01	0.04
Jadeite	**3.30**	**2.97**	**3.07**	**3.62**	**3.54**	**8.09**	**12.85**	**28.60**	**0.15**	**4.42**
Aeg.	**0.00**	**0.41**	**0.15**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.37**	**0.00**
Tsch.	**23.31**	**13.36**	**13.27**	**16.99**	**12.23**	**4.98**	**8.35**	**8.40**	**2.68**	**2.75**
Heden.	**3.72**	**1.12**	**2.44**	**3.26**	**4.82**	**17.77**	**4.86**	**4.74**	**1.61**	**6.80**
Diop.	**69.67**	**82.14**	**81.07**	**76.13**	**79.41**	**69.16**	**73.93**	**58.26**	**95.19**	**86.03**

TABLE IV.v (cont.)

	Ultrabasics				Eulysite		Marble		
	Web/D core	W1/2	301B/1	267/1	95/1	94/3	28/1.	54/2	59/1
SiO2	54.79	53.97	53.85	54.01	49.82	50.47	53.38	55.57	54.71
TiO2	0.04	0.04	0.04	0.17	0.05	0.01	0.19	0.09	0.06
Al2O3	0.92	1.65	2.62	2.38	0.33	0.22	3.94	0.30	2.17
Cr2O3	0.68	0.51	0.56	0.33	0.01	0.01	0.01	0.00	0.04
FeO	3.09	4.39	5.25	4.23	21.01	14.94	0.74	0.46	0.76
MnO	0.17	0.16	0.13	0.09	3.39	6.35	0.10	0.08	0.06
MgO	16.03	14.96	13.53	15.34	4.24	7.31	16.54	17.97	17.14
CaO	23.39	21.77	20.99	22.82	19.99	19.51	23.47	25.12	24.41
Na2O	0.77	1.60	2.15	0.90	0.83	0.61	0.76	0.15	0.53
Total	**99.87**	**99.04**	**99.10**	**100.28**	**99.68**	**99.42**	**99.14**	**99.74**	**99.88**
Si	2.00	1.98	1.98	1.97	1.99	1.99	1.94	2.01	1.98
Al(iv)	0.00	0.02	0.02	0.03	0.01	0.01	0.06	0.00	0.00
Al(vi)	0.04	0.05	0.09	0.07	0.01	0.00	0.11	0.01	0.09
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Fe'''	0.00	0.06	0.06	0.01	0.06	0.06	0.00	0.00	0.00
Cr	0.02	0.01	0.02	0.01	0.00	0.00	0.00	0.00	0.00
Fe''	0.09	0.07	0.10	0.12	0.64	0.43	0.02	0.01	0.02
Mn	0.01	0.00	0.00	0.00	0.11	0.21	0.00	0.00	0.00
Mg	0.87	0.82	0.74	0.83	0.25	0.43	0.89	0.97	0.92
Ca	0.91	0.86	0.83	0.89	0.86	0.82	0.91	0.97	0.94
Na	0.05	0.11	0.15	0.06	0.06	0.05	0.05	0.01	0.04
Jadeite	**3.91**	**5.45**	**9.49**	**6.38**	**0.75**	**0.00**	**5.36**	**1.05**	**3.71**
Aeg.	**1.51**	**5.91**	**5.81**	**0.00**	**5.70**	**4.63**	**0.00**	**0.00**	**0.00**
Tsch.	**0.30**	**1.69**	**1.80**	**3.22**	**0.74**	**1.26**	**6.03**	**0.24**	**2.90**
Heden.	**9.96**	**7.97**	**10.74**	**11.95**	**75.55**	**64.30**	**2.57**	**1.65**	**2.48**
Diop.	**84.32**	**78.98**	**72.15**	**78.45**	**17.27**	**29.81**	**86.04**	**97.07**	**90.90**

TABLE IV.vi : Representative analyses : W. L. Grt

	Eclogite						Amphib.	
	410/7	410/8	415/1	415/4	418/2	418/1	446/D	446/E
	core	rim	core	rim	core	rim	core	rim
SiO2	37.93	37.78	37.83	38.04	38.50	38.23	36.96	37.21
TiO2	0.06	0.05	0.05	0.05	0.07	0.06	0.27	0.13
Al2O3	20.82	20.67	20.94	21.07	21.14	21.09	20.52	20.65
Cr2O3	0.00	0.00	0.01	0.03	0.04	0.04	0.02	0.02
FeO	25.55	26.90	24.62	25.30	25.85	24.57	27.43	26.87
MnO	0.63	0.79	0.77	1.03	0.83	0.58	2.93	2.39
MgO	4.83	3.72	4.54	4.01	6.52	5.47	1.81	1.74
CaO	9.88	10.27	10.49	10.22	7.17	9.80	9.69	10.86
Total	99.74	100.21	99.28	99.77	100.12	99.87	99.71	99.90
Si	2.97	2.96	2.97	2.98	2.98	2.97	2.96	2.96
Al(iv)	0.03	0.04	0.03	0.02	0.02	0.03	0.04	0.04
Al(vi)	1.89	1.88	1.91	1.93	1.92	1.90	1.89	1.90
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01
Fe'''	0.14	0.15	0.11	0.07	0.09	0.12	0.12	0.12
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	1.53	1.61	1.50	1.59	1.58	1.48	1.72	1.67
Mn	0.04	0.05	0.05	0.07	0.05	0.04	0.20	0.16
Mg	0.56	0.44	0.53	0.47	0.75	0.63	0.22	0.21
Ca	0.83	0.86	0.88	0.86	0.60	0.82	0.83	0.93
Mg no.	0.27	0.21	0.26	0.23	0.32	0.30	0.11	0.11
Alm.	**51.71**	**54.39**	**50.66**	**53.19**	**53.06**	**49.88**	**57.98**	**56.37**
Spess.	**1.41**	**1.76**	**1.71**	**2.29**	**1.82**	**1.29**	**6.70**	**5.44**
Pyrope	**18.98**	**14.69**	**17.90**	**15.70**	**25.20**	**21.35**	**7.28**	**6.96**
Gross.	**20.95**	**21.48**	**23.99**	**24.93**	**15.09**	**21.47**	**21.39**	**24.99**
Uv.	**0.01**	**0.00**	**0.04**	**0.08**	**0.12**	**0.12**	**0.07**	**0.06**
Andr.	**6.94**	**7.67**	**5.70**	**3.80**	**4.71**	**5.90**	**6.58**	**6.18**

TABLE IV.vii : Rep. analyses : W. L. Cpx

	Eclogite							
	410/1	418/2	419/D	420/A	420/B	410/B	418/D	420/G
	core	core	core	core	rim	sym	sym	sym
SiO2	52.48	52.69	52.57	53.12	52.50	52.04	51.92	51.79
TiO2	0.25	0.22	0.23	0.21	0.26	0.22	0.30	0.22
Al2O3	6.37	8.52	8.29	8.01	7.27	3.64	3.88	4.40
Cr2O3	0.02	0.01	0.02	0.01	0.03	0.00	0.07	0.00
FeO	8.31	7.34	7.50	7.14	7.06	8.33	7.79	8.90
MnO	0.07	0.04	0.03	0.05	0.06	0.09	0.09	0.09
MgO	10.02	9.12	9.39	9.63	10.46	12.13	12.37	11.62
CaO	18.87	17.37	16.44	16.35	17.77	21.12	20.86	19.83
Na2O	3.37	4.56	4.61	4.58	3.75	1.48	1.92	2.14
Total	**99.77**	**99.90**	**99.09**	**99.11**	**99.15**	**99.10**	**99.21**	**99.01**
Si	1.93	1.91	1.92	1.94	1.92	1.94	1.93	1.93
Al(iv)	0.07	0.09	0.08	0.06	0.08	0.06	0.07	0.07
Al(vi)	0.20	0.28	0.28	0.29	0.24	0.10	0.09	0.12
Ti	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Fe'''	0.09	0.12	0.11	0.09	0.09	0.05	0.10	0.09
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	0.16	0.11	0.12	0.13	0.13	0.21	0.14	0.18
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.55	0.49	0.51	0.52	0.57	0.67	0.68	0.64
Ca	0.74	0.68	0.64	0.64	0.70	0.84	0.83	0.79
Na	0.24	0.32	0.33	0.32	0.27	0.11	0.14	0.15
Jadeite	**20.36**	**27.83**	**28.01**	**28.53**	**23.83**	**10.25**	**9.47**	**12.16**
Aeg.	**3.67**	**4.28**	**4.65**	**3.93**	**2.80**	**0.44**	**4.32**	**3.27**
Tsch.	**6.91**	**8.39**	**7.47**	**5.69**	**7.23**	**5.59**	**7.10**	**6.95**
Heden.	**16.23**	**10.68**	**11.87**	**13.25**	**12.92**	**21.07**	**14.45**	**18.57**
Diop,	**52.83**	**48.83**	**47.99**	**48.60**	**53.21**	**62.66**	**64.67**	**59.04**

TABLE IV.viii : Representative analyses : W. Lew. Amph

Eclogite

	407/7 gnt alt.	407/4 crack	414/4A	414/5 cpx alt.	415/2 cpx alt.	417/A	418/4 rim	418/5 crack	419/A	420/1 gnt alt.
SiO2	42.42	48.90	51.98	41.26	40.51	41.79	42.22	52.22	49.92	40.54
TiO2	0.37	0.64	0.05	0.61	1.28	1.01	0.96	0.18	0.30	0.28
Al2O3	13.26	7.35	1.78	13.15	13.59	12.56	13.02	2.06	5.44	15.04
Cr2O3	0.02	0.03	0.01	0.01	0.04	0.03	0.01	0.02	0.04	0.04
FeO	15.67	12.43	19.39	18.84	16.46	16.39	14.19	18.37	13.80	17.11
MnO	0.11	0.14	0.39	0.34	0.21	0.08	0.06	0.41	0.10	0.14
MgO	10.37	14.14	11.30	8.48	9.42	10.27	11.11	11.64	12.98	8.66
CaO	11.57	12.08	12.30	11.00	10.98	10.76	11.35	12.25	13.39	11.42
Na2O	2.18	1.42	0.37	2.07	2.05	2.34	2.27	0.30	0.89	2.24
K2O	0.82	0.51	0.15	1.30	2.06	1.47	1.86	0.10	0.19	0.93
Total	**96.79**	**97.62**	**97.71**	**97.05**	**96.60**	**96.91**	**97.05**	**97.55**	**97.16**	**96.40**
Si	6.34	7.09	7.72	6.24	6.16	6.28	6.32	7.73	7.41	6.14
Al (iv)	1.66	0.91	0.28	1.76	1.84	1.72	1.68	0.27	0.59	1.86
Al (vi)	0.68	0.35	0.04	0.59	0.59	0.51	0.63	0.09	0.36	0.83
Ti	0.04	0.07	0.01	0.07	0.15	0.11	0.11	0.02	0.03	0.03
Fe'''	0.41	0.18	0.18	0.61	0.37	0.55	0.18	0.16	-0.40	0.43
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	1.55	1.33	2.23	1.78	1.72	1.51	1.60	2.12	2.11	1.74
Mn	0.01	0.02	0.05	0.04	0.03	0.01	0.01	0.05	0.01	0.02
Mg	2.31	3.06	2.50	1.91	2.13	2.30	2.48	2.57	2.87	1.95
Ca	1.87	1.88	1.97	1.81	1.80	1.75	1.83	1.95	2.11	1.87
Na	0.64	0.40	0.11	0.61	0.61	0.69	0.66	0.09	0.25	0.66
K	0.16	0.09	0.03	0.25	0.40	0.28	0.36	0.02	0.04	0.18

Biotite amph. / Garnet amphibolite

	420/2 cpx alt.	420/6 crack	Biotite amph. 374/1	Biotite amph. 449/2	Garnet amphibolite RC3/1	RC3/B	446/4	447/1
SiO2	43.22	39.96	41.53	43.11	39.66	37.78	41.54	42.60
TiO2	0.14	0.33	0.72	0.67	0.89	0.36	0.73	0.67
Al2O3	11.47	16.73	12.81	12.89	13.16	16.40	14.17	13.18
Cr2O3	0.00	0.06	0.04	0.00	0.01	0.04	0.01	0.05
FeO	17.37	16.20	18.49	15.90	21.99	23.01	19.47	16.75
MnO	0.13	0.09	0.40	0.30	0.22	0.40	0.25	0.29
MgO	9.91	8.96	8.01	9.86	6.29	4.14	7.35	8.99
CaO	11.66	11.26	11.21	11.18	10.52	11.03	11.17	11.42
Na2O	1.84	2.60	1.94	2.10	2.30	1.88	2.04	2.02
K2O	0.68	0.95	1.09	1.06	1.06	1.06	1.23	0.84
Total	**96.42**	**97.12**	**96.24**	**97.07**	**96.10**	**96.12**	**97.96**	**96.80**
Si	6.51	5.97	6.36	6.44	6.15	5.90	6.26	6.41
Al (iv)	1.49	2.03	1.64	1.56	1.85	2.10	1.74	1.59
Al (vi)	0.55	0.92	0.67	0.71	0.56	0.93	0.78	0.76
Ti	0.02	0.04	0.08	0.07	0.10	0.04	0.08	0.08
Fe'''	0.47	0.49	0.35	0.32	0.69	0.61	0.35	0.24
Cr	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01
Fe	1.72	1.54	2.02	1.66	2.17	2.40	2.10	1.87
Mn	0.02	0.01	0.05	0.04	0.03	0.05	0.03	0.04
Mg	2.23	2.00	1.83	2.19	1.45	0.96	1.65	2.02
Ca	1.90	1.82	1.85	1.80	1.77	1.87	1.82	1.85
Na	0.54	0.76	0.58	0.61	0.70	0.58	0.60	0.59
K	0.13	0.18	0.21	0.20	0.21	0.21	0.24	0.16

TABLE IV.viii (cont.)

Plagioclase amphibolite

	358/1	372/1	423/1	452/1	452/2 crack	369/1	459/3	258/3	359/2	366/5
SiO2	40.88	44.12	41.02	42.11	49.94	43.95	42.93	45.51	41.33	41.01
TiO2	1.18	0.47	0.50	0.70	0.09	0.25	0.48	0.46	0.71	0.69
Al2O3	13.26	10.49	13.13	13.06	1.22	13.04	13.45	12.29	13.52	13.56
Cr2O3	0.02	0.09	0.00	0.02	0.00	0.09	0.04	0.09	0.04	0.08
FeO	16.75	15.04	20.27	17.96	23.50	13.93	15.73	12.31	17.11	20.00
MnO	0.30	0.30	0.41	0.29	0.54	0.29	0.25	0.32	0.31	0.39
MgO	9.15	11.40	7.23	8.81	8.98	11.72	9.62	12.62	9.30	7.37
CaO	11.20	11.81	11.10	11.39	11.66	11.42	11.52	11.44	11.35	10.80
Na2O	2.08	1.55	1.81	1.88	0.18	2.08	1.58	2.01	2.08	2.26
K2O	1.09	0.94	0.70	1.20	0.14	0.71	0.61	0.45	1.10	1.16
Total	**95.90**	**96.22**	**96.17**	**97.41**	**96.26**	**97.46**	**96.21**	**97.49**	**96.85**	**97.32**
Si	6.23	6.61	6.28	6.33	7.64	6.42	6.42	6.59	6.23	6.23
Al (iv)	1.77	1.39	1.72	1.67	0.36	1.58	1.58	1.41	1.77	1.77
Al (vi)	0.61	0.47	0.65	0.65	-0.14	0.67	0.80	0.69	0.63	0.65
Ti	0.14	0.05	0.06	0.08	0.01	0.03	0.05	0.05	0.08	0.08
Fe'''	0.41	0.38	0.65	0.42	0.57	0.55	0.40	0.42	0.49	0.55
Cr	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01
Fe	1.73	1.50	1.94	1.84	2.44	1.16	1.57	1.07	1.66	1.99
Mn	0.04	0.04	0.05	0.04	0.07	0.04	0.03	0.04	0.04	0.05
Mg	2.08	2.55	1.65	1.97	2.05	2.55	2.14	2.72	2.09	1.67
Ca	1.85	1.91	1.85	1.85	1.94	1.81	1.86	1.79	1.85	1.78
Na	0.62	0.45	0.54	0.55	0.05	0.60	0.46	0.57	0.61	0.67
K	0.21	0.18	0.14	0.23	0.03	0.13	0.12	0.08	0.21	0.23

TABLE IV.viii (cont.)

"Hbl - ite"

	373/1	450/C	RC1/4	370/1	443/1	458/1	425/1	424/5
SiO2	43.50	46.55	46.03	48.03	48.54	48.75	49.87	45.74
TiO2	0.54	0.41	0.39	0.43	0.27	0.26	0.34	0.59
Al2O3	11.02	9.23	8.78	7.39	8.31	9.73	5.31	8.04
Cr2O3	0.26	0.32	0.20	0.14	0.12	0.27	0.04	0.13
FeO	16.58	13.43	15.47	12.66	11.35	10.82	13.68	16.66
MnO	0.30	0.29	0.28	0.27	0.23	0.28	0.32	0.32
MgO	9.92	12.55	11.66	14.19	14.26	14.29	14.22	11.55
CaO	11.21	11.15	10.94	11.56	12.16	11.46	11.62	10.97
Na2O	1.95	1.72	1.69	1.67	1.21	1.54	1.43	1.99
K2O	0.85	0.54	0.44	0.25	0.25	0.40	0.68	0.99
Total	**96.11**	**96.19**	**95.86**	**96.58**	**96.70**	**97.81**	**97.51**	**96.96**
Si	6.58	6.86	6.85	7.01	7.04	6.95	7.26	6.82
Al (iv)	1.42	1.14	1.15	0.99	0.96	1.05	0.74	1.18
Al (vi)	0.54	0.47	0.39	0.28	0.47	0.58	0.17	0.23
Ti	0.06	0.04	0.04	0.05	0.03	0.03	0.04	0.07
Fe'''	0.37	0.43	0.60	0.48	0.25	0.39	0.34	0.53
Cr	0.03	0.04	0.02	0.02	0.01	0.03	0.00	0.02
Fe	1.73	1.23	1.33	1.06	1.13	0.90	1.33	1.55
Mn	0.04	0.04	0.03	0.03	0.03	0.03	0.04	0.04
Mg	2.23	2.76	2.59	3.08	3.08	3.04	3.08	2.57
Ca	1.83	1.78	1.77	1.83	1.90	1.76	1.83	1.77
Na	0.57	0.50	0.49	0.48	0.34	0.43	0.41	0.58
K	0.17	0.10	0.08	0.05	0.05	0.07	0.13	0.19

"Act - ite"

	367/1A core	367/1C >	367/1R rim	429/5	432/3 "hbl"	432/2 "act"	456/B
SiO2	53.83	50.74	54.85	49.14	50.78	55.19	48.85
TiO2	0.11	0.20	0.06	0.28	0.14	0.03	0.21
Al2O3	2.95	5.45	1.85	7.35	5.84	2.11	6.95
Cr2O3	0.27	0.83	0.21	0.08	0.27	0.13	0.32
FeO	7.20	7.91	6.30	10.34	9.33	7.75	9.45
MnO	0.26	0.26	0.20	0.24	0.28	0.30	0.25
MgO	18.77	16.91	19.38	15.09	16.65	18.91	15.87
CaO	11.45	11.82	12.45	12.32	12.06	12.23	11.69
Na2O	0.83	1.18	0.42	1.30	1.19	0.52	1.34
K2O	0.04	0.07	0.02	0.70	0.25	0.04	0.41
Total	**95.68**	**95.36**	**95.73**	**96.84**	**96.78**	**97.20**	**95.38**
Si	7.62	7.33	7.79	7.15	7.27	7.74	7.12
Al (iv)	0.38	0.67	0.21	0.85	0.73	0.26	0.88
Al (vi)	0.11	0.26	0.10	0.41	0.25	0.09	0.31
Ti	0.01	0.02	0.01	0.03	0.01	0.00	0.02
Fe'''	0.50	0.27	0.17	0.04	0.35	0.33	0.39
Cr	0.03	0.09	0.02	0.01	0.03	0.01	0.04
Fe	0.35	0.68	0.58	1.21	0.77	0.57	0.76
Mn	0.03	0.03	0.02	0.03	0.03	0.04	0.03
Mg	3.96	3.64	4.10	3.27	3.55	3.95	3.45
Ca	1.76	1.84	1.90	1.92	1.86	1.85	1.84
Na	0.23	0.33	0.12	0.37	0.33	0.14	0.38
K	0.01	0.01	0.00	0.13	0.05	0.01	0.08

APPENDIX V

Thermobarometry

The details of the thermobarometers used in chapter ten are as follows :
(T is in K, P is in bars unless otherwise specified)

1) Grt - Cpx (Fe - Mg exchange) : Krogh (1988) after Ellis and Green (1979)

$$1/3\ Mg_3Al_2Si_3O_{12} + CaFeSi_2O_6 \Leftrightarrow 1/3\ Fe_3Al_2Si_3O_{12} + CaMgSi_2O_6$$

$$T = \frac{(-6173((X_{Ca})^{Grt})^2 + 6731(X_{Ca})^{Grt} + 1879 + 10P(kb))}{(\ln K_D + 1.393)}$$

where $K_D = (Fe''/Mg)^{Grt} / (Fe''/Mg)^{Cpx}$

2) Grt - Bt (Fe - Mg exchange) : Indares and Martignole (1985)

$$1/3\ Mg_3Al_2Si_3O_{12} + K_2Fe_6Al_2Si_6O_{20}(OH,F)_4 \Leftrightarrow 1/3\ Fe_3Al_2Si_3O_{12} + K_2Mg_6Al_2Si_6O_{20}(OH,F)_4$$

$$T = \frac{12454 + 0.057P + 3(-1590(X_{Al})^{Bt} - 7451(X_{Ti})^{Bt}) - 3(-3000((X_{Ca})^{Grt} + (X_{Mn})^{Grt}))}{(4.662 - 5.9616\ln K_D)}$$

where $K_D = (Fe''/Mg)^{Bt} / (Fe''/Mg)^{Grt}$

3) Grt - Amph (Fe - Mg exchange) : Graham and Powell (1984)

$$1/4\ NaCa_2Fe_4Al_3Si_6O_{22}(OH)_2 + 1/3\ Mg_3Al_2Si_3O_{12} \Leftrightarrow 1/4\ NaCa_2Mg_4Al_3Si_6O_{22}(OH)_2 + 1/3\ Fe_3Al_2Si_3O_{12}$$

$$T = \frac{2880 + 3280(X_{Ca})^{Grt}}{\ln K_D + 2.426}$$

where $K_D = (Fe''/Mg)^{Grt} / (Fe''/Mg)^{Hbl}$

4) Plag - Amph : Blundy and Holland (1990)

$$NaCa_2Mg_4Al_3Si_6O_{22}(OH)_2 + 4SiO_2 \Leftrightarrow Ca_2Mg_4Al_2Si_7O_{22}(OH)_2 + NaAlSi_3O_8$$

$$T = \frac{0.677P - 48.98 + Y}{-0.0429 - 0.008314\ln K}$$

where $K = ((Si - 4)/(8 - Si))(X_{Alb})$
and $Y = 0$ if $(X_{Alb}) > 0.5$, $Y = -8.06 + 25.5(1 - (X_{Alb}))^2$ for $(X_{Alb}) < 0.5$

5) Jd + Qtz $\Leftrightarrow$ Alb : Holland (1980, 1983)

$$NaAlSi_2O_6 + SiO_2 \Leftrightarrow NaAlSi_3O_8$$

isopleths of X_{Jd}

6) Grt + Ky + Qtz ⇔ An : Koziol and Newton (1988)

$Ca_3Al_2Si_3O_{12} + Al_2SiO_5 + SiO_2 \Leftrightarrow 3CaAl_2Si_2O_8$

isopleths of log K_D, where $K_D = (a_{An})^3 / (a_{Gross})$

7) Sph + Ky ⇔ Rut + An : Manning and Bohlen (1991)

$CaTiSiO_5 + Al_2SiO_5 \Leftrightarrow CaAl_2Si_2O_8 + TiO_2$

isopleths of log K_D, where $K_D = (a_{An}) / (a_{Sph})$

8) Grt + Musc ⇔ Bt + An : Hodges and Spear (1982)

$$Ca_3Al_2Si_3O_{12} + Mg_3Al_2Si_3O_{12} + KAl_3Si_3O_{10}(OH)_2 \Leftrightarrow 3CaAl_2Si_2O_8 + KMg_3AlSi_3O_{10}(OH)_2$$

(and for $Fe_3Al_2Si_3O_{12}$ - $KFe_3AlSi_3O_{10}(OH)_2$)

for Mg end members : $P = \dfrac{8888.4 + 16.675T - RT\ln K_D}{1.738}$

for Fe end members : $P = \dfrac{-4124.4 + 22.061T - RT\ln K_D}{1.802}$

where $K_D = (X_{An})^3((X_{Mg})^{Bt})^3 / (X_{Musc})((X_{Mg})^{Grt})^3(X_{Ca})^{Grt})^3$
(and similar for Fe end members)

9) Plag + Al - poor Amph ⇔ Grt + Amph + Qtz : Kohn and Spear (1990)

$$6CaAl_2Si_2O_8 + 3\,Ca_2Mg_5Si_8O_{22}(OH)_2 \Leftrightarrow 2Ca_3Al_2Si_2O_{12} + Mg_3Al_2Si_2O_{12} + 3Ca_2Mg_4Al_2Si_7O_{22}(OH)_2 + 6SiO_2$$

(and similar for Fe end members)

$$P_{Mg} = \frac{79507 + T(29.14 + 8.3144\ln K_D)}{10.988}$$

$$P_{Fe} = \frac{35327 + T(56.09 + 8.3144\ln K_D)}{11.906}$$

where $K_D = \dfrac{(a_{Gross})^2(a_{Pyp})(a_{Tsch})^3}{(a_{An})^6(a_{Trem})^3}$
(and similar for Fe end members)

Where there parameters are calculated as follows :

$(X_{Fe})^{Grt} = Fe'' / (Fe'' + Mn + Mg + Ca)$

$(X_{Mg})^{Grt} = Mg / (Fe'' + Mn + Mg + Ca)$

$(X_{Mn})^{Grt} = Mn / (Fe'' + Mn + Mg + Ca)$

$(X_{Ca})^{Grt} = Ca / (Fe'' + Mn + Mg + Ca)$

$(X_{Al})^{Bt} = Al^{VI} / (Fe + Mn + Mg + Al^{VI} + Ti)$

$(X_{Ti})^{Bt} = Ti / (Fe + Mn + Mg + Al^{VI} + Ti)$

$(X_{Alb}) = Na / (Ca + Na + K)$

$(X_{An}) = Ca / (Ca + Na + K)$

$(X_{Musc}) = (K / (K + Ca + Na)) / (Al^{VI} / (Al^{VI} + Fe + Mn + Mg + Ti))^2$

$a_{Sph} = X_{Ca}X_{Ti}X_{Si}((5 - X_{Al} - X_{Fe'''}) / 5)^5$

[for eqn. 6)] :

$a_{An} = \gamma_{An} (((X_{Alb}) - (1 + (X_{an}))^2) / 4)$

$a_{Gross} = X_{Ca}\gamma_{Gross}$

[for eqn. 9)]

$a_{Pyp} = ((X_{Mg})e^{(((13800 - 6.28T)((X_{Ca})^2 + (X_{Fe})(X_{Ca}) + (X_{Ca})(X_{Mn}))) / RT)})^3$

$a_{Gross} = ((X_{Ca})e^{(((13800 - 6.28T)((X_{Mg})^2 + (X_{Fe})(X_{Mg}) + (X_{Mg})(X_{Mn}))) / RT)})^3$

$a_{Alm} = ((X_{Mg})e^{(((13800 - 6.28T)(- (X_{Mg})(X_{Ca})) / RT)})^3$

$a_{An} = (X)e^{((610.34 / T) - 0.3837)}$

$a_{Tsch} = (256/27)(X_{T1Al})(X_{T1Si})^3(Mg/(Fe'' + Mg))$

$a_{Trem} = (X_{T1Si})^4(Mg / (Fe'' + Mg))^2$

$a_{Fe\text{-}Tsch} = (256/27)(X_{T1Al})(X_{T1Si})^3(Fe'' /(Fe'' + Mg))$

$a_{Fe\text{-}Act} = (X_{T1Si})^4(Fe''/ (Fe'' + Mg))^2$

$X_{T1Si} = (Si_{Amph} -4) / 4$

$X_{T1Al} = (8 - Si_{Amph}) / 4$

Tables V.i - V.vii show representative analyses for minerals used to determine pressures and temperatures of metamorphism using the above thermobarometers. Table V.i is for garnet - clinopyroxene pairs from each of the Eastern Lewisian eclogites with the exception of the biotite eclogite, for two Eastern Lewisian marble nodules, and for the Western Lewisian eclogite. Table V.ii is for garnet - biotite pairs from selected Eastern Lewisian eclogites, Eastern Lewisian marble nodules and metapelites, Western Lewisian eclogites and the Moine. Table V.iii is for garnet - amphibole pairs selected from Eastern Lewisian eclogites, Eastern Lewisian marble nodules, Western Lewisian eclogites and Western Lewisian garnet - amphibolites. Table V.iv is for amphibolie - plagioclase pairs from Eastern Lewisian eclogites, Eastern Lewisian amphibolites, Western Lewisian eclogites, Western Lewisian garnet - amphibolites and Western Lewisian amphibolites. Table V.v is for garnet - plagioclase pairs within QFK streaks. Table V.vi is for sphene - plagioclase pairs. Table V.vii is for coexisting garnet - plagioclase - amphibole from Western Lewisian eclogite and Western Lewisian garnet - amphibolite.

Table V.i : Representative analyses : Grt - Cpx pairs Krogh (1988)

	Bimineralic Eclogite									
	E5/3	E5/3	E2/3	E2/9	E9/B/C	E9/B/C	264/1	264/2	96/3	96/3
					core	core				
	GRT	CPX	GRT	CPX	GRT	CPX	GRT	CPX	GRT	CPX
SiO2	38.90	53.37	38.95	53.76	38.985	54.211	39.10	53.89	38.557	53.997
TiO2	0.11	0.31	0.07	0.27	0.034	0.271	0.06	0.25	0.063	0.255
Al2O3	21.52	8.30	21.56	10.16	21.843	9.678	21.83	8.52	21.209	11.946
Cr2O3	0.10	0.14	0.03	0.02	0.064	0.043	0.09	0.07	0.000	0.000
FeO	20.93	4.87	20.03	4.28	20.877	4.344	20.31	4.76	21.656	4.759
MnO	0.60	0.05	0.68	0.05	0.963	0.091	0.61	0.05	0.450	0.035
MgO	8.96	10.79	8.31	9.56	8.407	10.062	9.05	10.49	7.347	7.975
CaO	8.49	17.39	9.84	16.30	9.269	16.627	8.78	17.40	9.696	13.956
Na2O	0.02	4.17	0.01	5.05	0.020	4.951	0.02	4.44	0.020	6.334
Total	**99.64**	**99.40**	**99.47**	**99.45**	**100.472**	**100.28**	**99.85**	**99.87**	**99.005**	**99.269**
Si	2.97	1.93	2.98	1.94	2.95	1.94	2.97	1.94	2.98	1.94
Al(iv)	0.03	0.07	0.02	0.06	0.05	0.06	0.03	0.06	0.02	0.06
Al(vi)	1.90	0.29	1.92	0.37	1.90	0.34	1.92	0.30	1.91	0.44
Ti	0.01	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
Fe'''	0.12	0.05	0.10	0.04	0.13	0.05	0.10	0.05	0.10	0.04
Cr	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Fe''	1.22	0.10	1.18	0.09	1.19	0.08	1.19	0.09	1.30	0.10
Mn	0.04	0.00	0.04	0.00	0.06	0.00	0.04	0.00	0.03	0.00
Mg	1.02	0.58	0.95	0.51	0.95	0.54	1.02	0.56	0.85	0.43
Ca	0.69	0.68	0.81	0.63	0.75	0.64	0.71	0.67	0.80	0.54
Na	0.00	0.29	0.00	0.35	0.00	0.34	0.00	0.31	0.00	0.44
X(Ca)	0.23		0.27		0.25		0.24		0.27	
Mg No.	45.50	85.86	44.43	84.56	44.41	86.65	46.24	86.01	39.41	81.34
Fe/Mg	1.20	0.16	1.25	0.18	1.25	0.15	1.16	0.16	1.54	0.23
Pyp/Jad	**34.28**	**28.74**	**31.76**	**35.25**	**32.16**	**34.29**	**34.50**	**30.22**	**28.40**	**44.09**
Alm/Aeg	**41.06**	**0.55**	**39.72**	**0.00**	**40.25**	**0.00**	**40.11**	**0.77**	**43.67**	**0.00**
Sps/Tsch	**1.30**	**6.29**	**1.48**	**5.36**	**2.09**	**5.97**	**1.33**	**5.62**	**0.99**	**5.67**
Gross	**17.06**		**21.98**		**18.63**		**18.74**		**21.88**	
And/Hed	**5.99**	**9.76**	**4.99**	**9.52**	**6.68**	**8.53**	**5.04**	**9.30**	**5.07**	**9.89**
Uv/Diop	**0.30**	**54.66**	**0.08**	**49.87**	**0.19**	**51.21**	**0.28**	**54.09**	**0.00**	**40.34**
K(D)	**7.27**		**6.85**		**8.12**		**7.15**		**6.70**	
(Kb)										
10	721		766		710		731		771	
12	726		772		715		737		777	
14	732		778		721		742		783	
16	738		783		726		748		789	
18	743		789		732		753		794	

Table V.i (cont.)

	Coarse Gnt		Orthopyroxene Eclogite					
	C4/4	C4/4	223/A/24	223/5	224/3	224/3	337/2	337/7
	core	core			host	incl	core	core
	GRT	CPX	GRT	CPX	GRT	CPX	GRT	CPX
SiO2	39.115	53.705	39.198	54.492	39.75	54.65	39.264	53.326
TiO2	0.091	0.099	0.044	0.258	0.05	0.26	0.086	0.172
Al2O3	21.637	2.148	22.082	9.697	22.23	10.07	21.616	3.064
Cr2O3	0.050	0.035	0.010	0.017	0.05	0.07	0.146	0.089
FeO	21.121	5.588	21.249	3.988	18.33	3.40	21.259	6.399
MnO	1.662	0.203	0.299	0.016	0.32	0.05	0.437	0.057
MgO	10.147	14.421	11.767	10.415	13.40	10.01	11.403	13.201
CaO	6.182	22.423	4.521	14.900	5.09	14.97	5.373	20.860
Na2O	0.021	1.268	0.032	5.982	0.02	5.80	0.035	2.142
Total	**100.03**	**99.90**	**99.211**	**99.765**	**99.24**	**99.29**	**99.63**	**99.31**
Si	2.96	1.97	2.96	1.94	2.97	1.95	2.97	1.96
Al(iv)	0.04	0.03	0.04	0.00	0.03	0.05	0.03	0.04
Al(vi)	1.90	0.06	1.94	0.41	1.93	0.38	1.89	0.09
Ti	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.00
Fe'''	0.13	0.03	0.09	0.01	0.10	0.02	0.12	0.06
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Fe''	1.21	0.14	1.25	0.11	1.05	0.08	1.22	0.14
Mn	0.11	0.01	0.02	0.00	0.02	0.00	0.03	0.00
Mg	1.15	0.79	1.33	0.55	1.49	0.53	1.28	0.72
Ca	0.50	0.88	0.37	0.57	0.41	0.57	0.43	0.82
Na	0.00	0.09	0.00	0.41	0.00	0.40	0.01	0.15
X(Ca)	0.17		0.12		0.14		0.15	
Mg No.	48.61	84.75	51.49	83.02	58.72	87.19	51.31	83.89
Fe/Mg	1.06	0.18	0.94	0.20	0.70	0.15	0.95	0.19
Pyp/Jad	**38.64**	**6.05**	**44.78**	**40.64**	**50.26**	**37.87**	**43.30**	**9.50**
Alm/Aeg	**40.84**	**2.96**	**42.20**	**0.57**	**35.34**	**2.33**	**41.09**	**5.79**
Sps/Tsch	**3.60**	**1.80**	**0.65**	**0.37**	**0.69**	**2.76**	**0.94**	**2.27**
Gross	**10.26**		**7.58**		**8.70**		**7.86**	
And/Hed	**6.51**	**14.80**	**4.77**	**11.33**	**4.86**	**7.98**	**6.38**	**14.08**
Uv/Diop	**0.15**	**74.39**	**0.03**	**47.09**	**0.15**	**49.06**	**0.43**	**68.37**
K(D)	**5.88**		**4.61**		**4.79**		**4.94**	
(Kb)								
10	724		754		755		754	
12	730		760		761		760	
14	736		766		767		766	
16	742		773		773		772	
18	748		779		780		778	

Table V.i (cont.)

	Quartz Eclogite							
	83/B/F	83/B/A	330/1	330/1	503/3	503/2	347/A/A	347/A/1
	rim	rim	host	incl	core	core		
	GRT	CPX	GRT	CPX	GRT	CPX	GRT	CPX
SiO2	38.32	51.26	38.24	53.49	38.897	52.778	39.064	52.472
TiO2	0.11	0.39	0.08	0.30	0.048	0.327	0.061	0.373
Al2O3	21.14	9.24	21.00	7.98	21.685	9.488	21.714	8.895
Cr2O3	0.04	0.04	0.05	0.05	0.020	0.046	0.097	0.047
FeO	21.38	6.18	24.12	6.24	20.610	4.966	20.461	5.305
MnO	0.33	0.05	0.42	0.04	0.416	0.011	0.352	0.052
MgO	5.88	9.87	6.30	10.08	8.141	9.973	7.819	10.527
CaO	12.45	18.78	8.89	17.24	9.783	17.686	10.579	18.400
Na2O	0.03	3.61	0.01	4.31	0.022	4.183	0.014	3.716
Total	**99.67**	**99.44**	**99.10**	**99.74**	**99.63**	**99.46**	**100.163**	**99.792**
Si	2.96	1.87	2.98	1.94	2.97	1.91	2.97	1.90
Al(iv)	0.04	0.13	0.02	0.06	0.03	0.09	0.03	0.10
Al(vi)	1.88	0.27	1.91	0.28	1.92	0.32	1.92	0.28
Ti	0.01	0.01	0.00	0.01	0.00	0.01	0.00	0.01
Fe'''	0.15	0.09	0.09	0.02	0.10	0.04	0.10	0.06
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Fe''	1.23	0.10	1.48	0.17	1.22	0.11	1.20	0.10
Mn	0.02	0.00	0.03	0.00	0.03	0.00	0.02	0.00
Mg	0.68	0.54	0.73	0.54	0.93	0.54	0.89	0.57
Ca	1.03	0.73	0.74	0.67	0.80	0.69	0.86	0.71
Na	0.00	0.26	0.00	0.30	0.00	0.29	0.00	0.26
X(Ca)	0.35		0.25		0.27		0.29	
Mg No.	35.45	84.91	33.04	76.44	43.26	83.30	42.46	84.49
Fe/Mg	1.82	0.18	2.03	0.31	1.31	0.20	1.36	0.18
Pyp/Jad	**22.86**	**25.59**	**24.51**	**28.16**	**31.20**	**29.40**	**29.82**	**26.11**
Alm/Aeg	**41.62**	**0.00**	**49.68**	**2.13**	**40.93**	**0.00**	**40.41**	**0.00**
Sps/Tsch	**0.73**	**12.36**	**0.92**	**3.46**	**0.91**	**8.22**	**0.76**	**9.35**
Gross	**27.09**		**20.03**		**21.79**		**23.60**	
And/Hed	**7.60**	**9.71**	**4.71**	**16.92**	**5.11**	**10.84**	**5.12**	**10.60**
Uv/Diop	**0.11**	**52.35**	**0.14**	**49.33**	**0.06**	**51.54**	**0.29**	**53.94**
K(D)	**10.24**		**6.58**		**6.54**		**7.38**	
(Kb)								
10	724		760		778		762	
12	729		765		784		768	
14	735		771		790		773	
16	740		777		795		779	
18	745		783		801		784	

Table V.i (cont.)

	Marble Nodules			
	313/2	313/5	263/1	263/4
	rim	rim		
	GRT	CPX	GRT	CPX
SiO2	39.103	49.349	38.655	51.261
TiO2	0.228	0.878	0.215	0.557
Al2O3	20.961	6.950	20.604	8.196
Cr2O3	0.016	0.016	0.071	0.000
FeO	10.011	3.658	14.434	4.499
MnO	0.772	0.106	1.220	0.073
MgO	4.986	13.493	4.015	11.332
CaO	22.901	24.063	19.754	20.716
Na2O	0.028	0.815	0.044	2.760
Total	**99.01**	**99.337**	**99.022**	**99.399**
Si	2.98	1.81	2.99	1.87
Al(iv)	0.02	0.19	0.01	0.13
Al(vi)	1.86	0.11	1.86	0.22
Ti	0.01	0.02	0.01	0.02
Fe'''	0.14	0.08	0.12	0.07
Cr	0.00	0.00	0.00	0.00
Fe''	0.50	0.03	0.81	0.07
Mn	0.05	0.00	0.08	0.00
Mg	0.57	0.74	0.46	0.62
Ca	1.87	0.95	1.64	0.81
Na	0.00	0.06	0.01	0.20
X(Ca)	0.63		0.55	
Mg No.	52.99	95.97	36.22	90.29
Fe/Mg	0.89	0.04	1.76	0.11
Pyp/Jad	**18.95**	**5.81**	**15.45**	**19.53**
Alm/Aeg	**16.81**	**0.00**	**27.21**	**0.00**
Sps/Tsch	**1.67**	**17.47**	**2.67**	**12.19**
Gross	**55.13**		**47.89**	
And/Hed	**7.40**	**3.43**	**6.56**	**6.85**
Uv/Diop	**0.05**	**73.30**	**0.22**	**61.43**
K(D)	**21.15**		**16.37**	
(Kb)				
10	752		756	
12	757		761	
14	761		765	
16	766		770	
18	770		775	

Table V.i (cont.)

	Western Lewisian Eclogite									
	252/19	252/16	418/2	418/1	420/A	420/A	420/B	420/B	418/2	418/1
	core	core	core	core	core	core	rim	rim	rim	rim
	GRT	CPX	GRT	CPX	GRT	CPX	GRT	CPX	GRT	CPX
SiO2	37.91	52.82	38.50	52.46	38.17	53.12	37.98	52.50	37.80	51.99
TiO2	0.04	0.28	0.07	0.24	0.06	0.21	0.05	0.26	0.05	0.16
Al2O3	21.05	6.98	21.14	8.05	20.90	8.01	21.01	7.27	20.65	5.99
Cr2O3	0.01	0.01	0.04	0.02	0.02	0.01	0.04	0.03	0.03	0.04
FeO	25.72	7.14	25.85	7.76	26.05	7.14	24.03	7.06	25.70	8.70
MnO	0.65	0.03	0.83	0.06	0.68	0.05	0.52	0.06	0.66	0.08
MgO	6.42	10.33	6.52	9.44	6.75	9.63	5.83	10.46	4.92	10.21
CaO	7.52	18.72	7.17	17.81	6.95	16.35	9.57	17.77	9.63	18.75
Na2O	0.02	3.45	0.00	4.18	0.02	4.58	0.03	3.75	0.03	3.11
Total	**99.36**	**99.75**	**100.12**	**100.04**	**99.60**	**99.11**	**99.05**	**99.15**	**99.49**	**99.03**
Si	2.96	1.93	2.98	1.91	2.97	1.94	2.97	1.92	2.96	1.93
Al(iv)	0.04	0.07	0.02	0.09	0.03	0.06	0.03	0.08	0.04	0.07
Al(vi)	1.90	0.23	1.92	0.25	1.89	0.29	1.91	0.24	1.88	0.19
Ti	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00
Fe'''	0.14	0.01	0.09	0.04	0.13	0.04	0.12	0.03	0.15	0.03
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	1.54	0.21	1.58	0.19	1.56	0.18	1.45	0.19	1.53	0.24
Mn	0.04	0.00	0.05	0.00	0.04	0.00	0.03	0.00	0.04	0.00
Mg	0.75	0.56	0.75	0.51	0.78	0.52	0.68	0.57	0.58	0.56
Ca	0.63	0.73	0.60	0.69	0.58	0.64	0.80	0.70	0.81	0.74
Na	0.00	0.24	0.00	0.29	0.00	0.32	0.00	0.27	0.00	0.22
X(Ca)	0.21		0.20		0.20		0.27		0.27	
Mg No.	32.70	73.22	32.20	72.45	33.35	74.56	31.85	75.22	27.27	70.58
Fe/Mg	2.06	0.37	2.11	0.38	2.00	0.34	2.14	0.33	2.67	0.42
Pyp/Jac	**25.27**	**23.21**	**25.20**	**25.36**	**26.33**	**28.53**	**22.88**	**23.83**	**19.42**	**18.91**
Alm/Ae(	**52.01**	**1.25**	**53.06**	**4.13**	**52.64**	**3.93**	**48.97**	**2.80**	**51.79**	**3.47**
Sps/Tsc	**1.45**	**3.84**	**1.82**	**4.96**	**1.51**	**3.30**	**1.15**	**4.19**	**1.48**	**3.92**
Gross	**14.22**		**15.09**		**12.79**		**20.91**		**19.60**	
And/He(	**7.03**	**20.68**	**4.71**	**19.65**	**6.66**	**18.02**	**5.97**	**19.00**	**7.62**	**23.77**
Uv/Diop	**0.02**	**51.02**	**0.12**	**45.90**	**0.06**	**46.21**	**0.12**	**50.17**	**0.09**	**49.93**
K(D)	**5.63**		**5.54**		**5.86**		**6.50**		**6.40**	
(Kb)										
10	773		766		747		781		787	
12	779		772		753		786		793	
14	785		778		759		792		799	
16	791		784		765		798		805	
18	797		790		771		804		810	

Table V.ii : Representative Grt - Bt analyses Indares & Martignole (1985)

	Eastern Lewisian Ec.						Biotite Eclog	
	E2/2	E2/3	96/4	96/4	Du4/A/A	Du4/1	512/5	512/2
	GRT	BT	GRT	BT	GRT	BT	GRT	BT
SiO2	38.99	37.68	38.46	36.49	38.26	36.66	37.97	36.92
TiO2	0.09	3.23	0.06	4.05	0.10	2.30	0.07	3.75
Al2O3	21.60	15.51	21.10	15.88	20.79	16.16	21.10	14.64
Cr2O3	0.02	0.04	0.01	0.08	0.10	0.23	0.04	0.02
FeO	20.04	11.84	19.55	14.41	22.71	15.59	28.27	13.41
MnO	0.68	0.09	0.47	0.11	0.66	0.18	0.52	0.02
MgO	8.35	16.42	5.83	13.51	5.75	12.96	7.70	15.48
CaO	9.97	0.02	13.13	0.03	11.00	0.07	3.88	0.05
Na2O	0.03	0.17	0.02	0.08	0.03	0.17	0.02	0.44
K2O	0.01	9.40	0.00	8.69	0.00	8.16	0.02	9.01
Total	**99.78**	**94.41**	**98.63**	**93.32**	**99.40**	**92.47**	**99.59**	**93.74**
Si	2.97	5.68	2.99	5.64	2.97	5.69	2.96	5.66
Al(iv)	0.03	2.32	0.01	2.36	0.03	2.31	0.04	2.34
Al(vi)	1.91	0.44	1.92	0.53	1.88	0.66	1.90	0.31
Ti	0.01	0.37	0.00	0.47	0.01	0.27	0.00	0.43
Fe'''	0.11	0.09	0.08	-0.06	0.13	0.20	0.14	0.07
Cr	0.00	0.01	0.00	0.01	0.01	0.03	0.00	0.00
Fe''	1.16	1.51	1.19	2.06	1.35	1.98	1.70	1.78
Mn	0.04	0.01	0.03	0.02	0.04	0.03	0.03	0.00
Mg	0.95	3.96	0.67	3.33	0.67	3.23	0.89	3.80
Ca	0.81	0.00	1.09	0.00	0.92	0.01	0.32	0.01
Na	0.00	0.05	0.00	0.03	0.00	0.06	0.00	0.14
K	0.00	1.94	0.00	1.83	0.00	1.74	0.00	1.89
X(Ca)	0.27	X(Al)	0.37	X(Al)	0.31	X(Al)	0.11	X(Al)
Mg No.	44.89	0.07	36.17	0.08	33.05	0.11	34.40	0.05
Fe'''/Fe''(%	9.66	X(Ti)	6.67	X(Ti)	9.40	X(Ti)	8.05	X(Ti)
		0.06		0.07		0.04		0.07
Fe/Mg	1.23	0.38	1.76	0.62	2.03	0.61	1.91	0.47
Pyp	**31.93**		**22.57**		**22.39**		**30.23**	
Alm	**39.20**		**39.83**		**45.36**		**57.66**	
Spess	**1.47**		**1.03**		**1.47**		**1.16**	
Gross	**21.53**		**32.40**		**23.91**		**3.90**	
And	**5.81**		**4.14**		**6.58**		**6.92**	
Uv	**0.07**		**0.03**		**0.30**		**0.13**	
X(Mn)	0.01		0.01		0.01		0.01	
K(D)		0.31		0.35		0.30		0.25
ln K(D)		-1.17		-1.05		-1.20		-1.40
Temp.								
Pressure (Kb)		I&M		I&M		I&M		I&M
10		757		696		732		781
12		766		706		742		790
14		776		717		751		799
16		786		727		761		807
18		796		738		771		816

Table V.ii (cont.)

	Marble Nodules				Eastern Lewisian Metasediments					
	261/2	261/1	260/4	260/1	10/5.	10/3.	8:Grt2 core	8:Bt2 core	98/10 rim	98/1 rim
	GRT	BT	GRT	BT	GRT	BT	GRT	BT	GRT	BT
SiO2	37.13	35.44	37.26	36.19	38.30	38.39	37.34	35.55	37.59	35.34
TiO2	0.06	2.39	0.04	4.84	0.04	0.45	0.02	1.45	0.04	1.33
Al2O3	19.87	13.46	19.89	13.20	21.57	16.29	20.99	18.25	20.97	19.12
Cr2O3	0.04	0.05	0.02	0.04	0.11	0.11	0.07	0.20	0.03	0.11
FeO	32.57	20.47	35.30	20.89	25.42	11.87	30.56	17.00	30.52	17.27
MnO	3.34	0.18	0.71	0.09	0.31	0.02	0.59	0.06	0.94	0.06
MgO	3.93	12.41	4.15	10.31	8.62	16.89	4.64	11.87	4.47	11.45
CaO	2.55	0.15	2.25	0.07	4.57	0.03	5.18	0.05	5.42	0.03
Na2O	0.06	0.11	0.02	0.08	0.03	0.08	0.05	0.16	0.03	0.31
K2O	0.00	9.18	0.00	9.22	0.03	9.20	0.01	8.99	0.02	8.67
Total	**99.54**	**93.84**	**99.64**	**94.93**	**99.00**	**93.31**	**99.44**	**93.58**	**100.02**	**93.68**
Si	2.99	5.58	3.00	5.73	2.97	5.77	2.96	5.51	2.97	5.46
Al(iv)	0.01	2.42	0.00	2.27	0.03	2.23	0.04	2.49	0.03	2.54
Al(vi)	1.87	0.08	1.88	0.20	1.94	0.66	1.93	0.85	1.92	0.95
Ti	0.00	0.28	0.00	0.58	0.00	0.05	0.00	0.17	0.00	0.15
Fe'''	0.13	0.66	0.12	-0.21	0.08	0.48	0.10	0.24	0.10	0.26
Cr	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.03	0.00	0.01
Fe''	2.06	2.27	2.26	3.16	1.57	1.14	1.93	2.13	1.92	2.15
Mn	0.23	0.03	0.05	0.01	0.02	0.00	0.04	0.01	0.06	0.01
Mg	0.47	3.17	0.50	2.60	1.00	4.10	0.55	2.95	0.53	2.84
Ca	0.22	0.03	0.19	0.01	0.38	0.01	0.44	0.01	0.46	0.00
Na	0.01	0.04	0.00	0.02	0.00	0.02	0.01	0.05	0.00	0.10
K	0.00	2.01	0.00	1.99	0.00	1.91	0.00	1.92	0.00	1.84
X(Ca)	0.07	X(Al)	0.06	X(Al)	0.13	X(Al)	0.15	X(Al)	0.15	X(Al)
Mg No.	18.60	0.01	18.04	0.03	38.85	0.11	22.19	0.14	21.52	0.16
Fe'''/Fe''(%	6.20	X(Ti)	5.19	X(Ti)	5.13	X(Ti)	5.31	X(Ti)	5.16	X(Ti)
		0.05		0.09		0.01		0.03		0.03
Fe/Mg	4.38	0.72	4.54	1.22	1.57	0.28	3.51	0.72	3.65	0.75
Pyp	**15.81**		**16.58**		**33.61**		**18.58**		**17.74**	
Alm	**69.20**		**75.35**		**52.89**		**65.16**		**64.67**	
Spess	**7.63**		**1.61**		**0.68**		**1.35**		**2.12**	
Gross	**0.69**		**0.42**		**8.39**		**9.63**		**10.37**	
And	**6.55**		**5.97**		**4.09**		**5.08**		**5.00**	
Uv	**0.11**		**0.07**		**0.34**		**0.20**		**0.10**	
X(Mn)	0.08		0.02		0.01		0.01		0.02	
K(D)		0.16		0.27		0.18		0.21		0.21
ln K(D)		-1.81		-1.32		-1.73		-1.58		-1.58
Temp.										
Pressure		I&M		I&M		I&M		I&M		I&M
(Kb)										
10		681		814		739		730		721
12		688		823		747		738		729
14		696		832		755		746		737
16		703		841		762		754		745
18		710		850		770		762		753

Table V.ii (cont.)

	Eastern Lewisian Metasediments (cont.)									
	316/4	316/4	86/4	86/3	8:gnt4	8:biot4	7/4. rim	7/2. rim	86/1	86/1
	GRT	BT	GRT	BT	GRT	BT	GRT	BT	GRT	BT
SiO2	38.28	37.37	37.19	36.90	37.26	36.67	37.57	37.17	37.19	38.31
TiO2	0.06	4.09	0.03	1.40	0.03	1.27	0.04	1.36	0.03	1.31
Al2O3	21.28	14.57	20.86	18.60	20.87	17.85	21.08	19.36	20.88	17.87
Cr2O3	0.07	0.09	0.07	0.05	0.05	0.05	0.06	0.08	0.01	0.04
FeO	29.06	16.30	31.66	13.77	30.52	16.22	31.97	15.44	30.19	14.99
MnO	0.47	0.06	0.74	0.02	0.62	0.06	0.67	0.04	0.76	0.04
MgO	5.92	11.54	5.83	13.96	4.50	12.72	4.50	14.08	4.55	13.60
CaO	5.14	0.12	2.55	0.01	5.20	0.12	4.32	0.01	5.56	0.07
Na2O	0.02	0.09	0.03	0.15	0.04	0.22	0.02	0.47	0.04	0.16
K2O	0.02	9.32	0.02	9.25	0.00	8.62	0.02	8.51	0.01	8.37
Total	**100.33**	**93.54**	**98.98**	**94.09**	**99.08**	**93.80**	**100.23**	**96.53**	**99.24**	**94.75**
Si	2.99	5.91	2.96	5.60	2.97	5.62	2.97	5.48	2.96	5.75
Al(iv)	0.01	2.09	0.04	2.40	0.03	2.38	0.03	2.52	0.04	2.25
Al(vi)	1.94	0.62	1.92	0.93	1.93	0.85	1.94	0.84	1.92	0.92
Ti	0.00	0.49	0.00	0.16	0.00	0.15	0.00	0.15	0.00	0.15
Fe'''	0.06	-0.67	0.11	0.12	0.09	0.25	0.09	0.45	0.12	0.17
Cr	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00
Fe''	1.83	2.95	2.00	1.76	1.95	2.00	2.03	1.61	1.89	1.85
Mn	0.03	0.01	0.05	0.00	0.04	0.01	0.04	0.01	0.05	0.01
Mg	0.69	2.87	0.69	3.39	0.53	3.13	0.53	3.34	0.54	3.27
Ca	0.43	0.02	0.22	0.00	0.44	0.02	0.37	0.00	0.47	0.01
Na	0.00	0.03	0.01	0.05	0.01	0.07	0.00	0.15	0.01	0.05
K	0.00	1.98	0.00	1.92	0.00	1.82	0.00	1.73	0.00	1.72
X(Ca)	0.14	X(Al)	0.07	X(Al)	0.15	X(Al)	0.12	X(Al)	0.16	X(Al)
Mg No.	27.29	0.09	25.73	0.15	21.55	0.14	20.72	0.14	22.22	0.15
Fe'''/Fe''(%	3.32	X(Ti)	5.58	X(Ti)	4.57	X(Ti)	4.29	X(Ti)	6.39	X(Ti)
		0.07		0.03		0.02		0.03		0.02
Fe/Mg	2.66	1.03	2.89	0.52	3.64	0.64	3.83	0.48	3.50	0.57
Pyp	**23.07**		**23.40**		**18.02**		**17.85**		**18.27**	
Alm	**61.48**		**67.56**		**65.61**		**68.31**		**63.94**	
Spess	**1.04**		**1.68**		**1.40**		**1.51**		**1.74**	
Gross	**11.00**		**1.58**		**10.34**		**7.76**		**10.01**	
And	**3.21**		**5.56**		**4.47**		**4.39**		**6.01**	
Uv	**0.20**		**0.23**		**0.16**		**0.18**		**0.04**	
X(Mn)	0.01		0.02		0.01		0.02		0.02	
K(D)		0.39		0.18		0.18		0.13		0.16
ln K(D)		-0.95		-1.72		-1.74		-2.07		-1.82
Temp.										
Pressure (Kb)		I&M		I&M		I&M		I&M		I&M
10		931		733		688		619		656
12		942		741		695		626		663
14		953		748		703		632		671
16		964		756		711		639		678
18		975		764		718		646		685

Table V.ii (cont.)

	E.L. Sed.		Western Lewisian Ec.				Moine			
	243/18	243/4	418/3	418/1	417/3	417/1	100/Br rim	100/A rim	A1/1	A1/1
	GRT	BT	GRT	BT	GRT	BT	GRT	BT	GRT	BT
SiO2	36.83	35.58	38.11	36.62	37.89	35.19	37.07	36.69	37.19	35.29
TiO2	0.04	2.05	0.11	2.79	0.08	2.94	0.08	1.80	0.04	1.87
Al2O3	20.48	16.89	20.64	16.18	20.92	15.00	20.74	17.62	20.33	18.63
Cr2O3	0.19	0.22	0.06	0.10	0.01	0.03	0.00	0.03	0.06	0.08
FeO	31.70	21.00	24.88	15.46	25.40	16.93	31.71	17.84	30.61	18.57
MnO	3.30	0.19	0.56	0.05	0.70	0.05	0.13	0.02	1.09	0.09
MgO	2.70	9.43	5.71	13.92	5.51	12.62	3.10	10.67	3.29	10.37
CaO	4.38	0.05	9.29	0.07	8.88	0.05	6.91	0.31	6.56	0.02
Na2O	0.01	0.08	0.03	0.21	0.02	0.17	0.04	0.20	0.03	0.19
K2O	0.03	7.31	0.02	8.23	0.00	7.02	0.01	8.15	0.01	8.88
Total	**99.65**	**92.79**	**99.41**	**93.62**	**99.39**	**89.99**	**99.78**	**93.33**	**99.19**	**93.97**
Si	2.97	5.60	2.98	5.60	2.97	5.59	2.96	5.73	2.98	5.50
Al(iv)	0.03	2.40	0.02	2.40	0.03	2.41	0.04	2.27	0.02	2.50
Al(vi)	1.92	0.73	1.88	0.51	1.90	0.40	1.91	0.97	1.91	0.93
Ti	0.00	0.24	0.01	0.32	0.00	0.35	0.00	0.21	0.00	0.22
Fe'''	0.10	0.47	0.13	0.36	0.13	0.63	0.13	-0.11	0.10	0.10
Cr	0.01	0.03	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01
Fe''	2.04	2.52	1.50	1.77	1.53	1.81	1.99	2.60	1.95	2.50
Mn	0.23	0.03	0.04	0.01	0.05	0.01	0.01	0.00	0.07	0.01
Mg	0.32	2.39	0.67	3.42	0.64	3.25	0.37	2.65	0.39	2.59
Ca	0.38	0.01	0.78	0.01	0.74	0.01	0.59	0.05	0.56	0.00
Na	0.00	0.03	0.00	0.07	0.00	0.06	0.01	0.07	0.00	0.06
K	0.00	1.59	0.00	1.73	0.00	1.55	0.00	1.73	0.00	1.90
X(Ca)	0.13	X(Al)	0.26	X(Al)	0.25	X(Al)	0.20	X(Al)	0.19	X(Al)
Mg No.	13.74	0.12	30.75	0.09	29.51	0.07	15.66	0.15	16.81	0.15
Fe'''/Fe''(%	4.85	X(Ti)	8.49	X(Ti)	8.36	X(Ti)	6.49	X(Ti)	5.37	X(Ti)
		0.04		0.05		0.06		0.03		0.04
Fe/Mg	6.28	1.05	2.25	0.52	2.39	0.56	5.38	0.98	4.95	0.97
Pyp	**10.95**		**22.34**		**21.64**		**12.49**		**13.21**	
Alm	**68.71**		**50.31**		**51.71**		**67.23**		**65.40**	
Spess	**7.60**		**1.25**		**1.56**		**0.29**		**2.48**	
Gross	**7.17**		**19.29**		**18.51**		**13.45**		**13.43**	
And	**4.98**		**6.62**		**6.56**		**6.55**		**5.30**	
Uv	**0.58**		**0.19**		**0.02**		**0.00**		**0.18**	
X(Mn)	0.08		0.01		0.02		0.00		0.02	
K(D)		0.17		0.23		0.23		0.18		0.20
ln K(D)		-1.78		-1.47		-1.45		-1.70		-1.63
Temp.										
Pressure (Kb)		I&M		I&M		I&M		I&M		I&M
10		633		668		671		658		667
12		641		677		680		665		675
14		648		685		688		673		683
16		656		694		697		681		691
18		663		702		705		688		699

Table V.iii : Representative analyses : Grt - Am pairs
Graham & Powell (1984)

Bimineralic Eclogite

	353/2	353/6 prim.	E2/A/2	E2/A/2	E10/iii	E10/iii prim.	E9/1	E9/1 prim.	353/2	353/6 prim.
	GRT	AM	GRT	AM	GRT	AM	GRT	AM	GRT	AM
SiO2	39.04	44.01	38.93	42.36	39.06	40.49	38.09	39.76	39.04	44.01
TiO2	0.06	0.62	0.04	1.32	0.04	0.59	0.06	0.22	0.06	0.62
Al2O3	21.28	11.18	21.74	14.74	21.28	18.11	21.27	16.95	21.28	11.18
Cr2O3	0.00	0.07	0.05	0.08	0.06	0.08	0.07	0.08	0.00	0.07
FeO	19.90	13.81	20.58	10.35	22.12	12.69	22.62	13.20	19.90	13.81
MnO	0.45	0.10	0.77	0.11	0.72	0.21	1.34	0.27	0.45	0.10
MgO	9.36	12.65	8.10	12.79	7.86	9.92	6.57	10.00	9.36	12.65
CaO	9.16	11.74	9.81	10.83	8.20	11.00	9.02	11.45	9.16	11.74
Na2O	0.02	1.76	0.02	2.81	0.03	3.43	0.02	2.71	0.02	1.76
K2O	0.00	0.73	0.00	1.38	0.00	0.58	0.00	1.16	0.00	0.73
Total	**99.26**	**96.65**	**100.05**	**96.76**	**99.36**	**97.09**	**99.06**	**95.79**	**99.26**	**96.65**
Si	2.97	6.49	2.96	6.21	3.01	5.99	2.96	6.00	2.97	6.49
Al(iv)	0.03	1.51	0.04	1.79	0.00	2.01	0.04	2.00	0.03	1.51
Al(vi)	1.89	0.43	1.91	0.76	1.93	1.14	1.92	1.02	1.89	0.43
Ti	0.00	0.07	0.00	0.15	0.00	0.07	0.00	0.02	0.00	0.07
Fe'''	0.13	0.59	0.12	0.26	0.04	0.70	0.11	0.72	0.13	0.91
Cr	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
Fe''	1.14	1.11	1.19	1.01	1.38	0.87	1.36	0.95	1.14	0.79
Mn	0.03	0.01	0.05	0.01	0.05	0.03	0.09	0.03	0.03	0.01
Mg	1.06	2.78	0.92	2.80	0.90	2.19	0.76	2.25	1.06	2.78
Ca	0.75	1.88	0.80	1.71	0.68	1.77	0.75	1.88	0.75	1.89
Na	0.00	0.51	0.00	0.80	0.00	1.00	0.00	0.80	0.00	0.51
K	0.00	0.14	0.00	0.26	0.00	0.11	0.00	0.23	0.00	0.14
X(Ca)	0.25		0.27		0.23		0.25		0.25	
Mg No.	48.35	71.48	43.48	73.54	39.50		35.86		48.35	
Fe/Mg	1.07	0.40	1.30	0.36	1.53	0.40	1.79	0.42	1.07	0.28
Pyp	**35.72**		**31.01**		**29.99**		**25.70**		**35.72**	
Alm	**38.16**		**40.32**		**45.94**		**45.96**		**38.16**	
Spess	**0.98**		**1.67**		**1.55**		**2.98**		**0.98**	
Gross	**18.42**		**21.06**		**19.99**		**19.59**		**18.42**	
Andr	**6.72**		**5.79**		**2.33**		**5.57**		**6.72**	
Uv	**0.00**		**0.15**		**0.19**		**0.20**		**0.00**	
K(D)	2.68		3.61		3.87		4.25		3.76	
T(C)	801		726		665		667		697	

Table V.iii (cont.)

	Bi. Ec. (cont)		Coarse Garnet				Quartz Ec.		Marble Nod.	
	E3/1	E3/1 prim.	C3/5	C3/3 vein	C5/6	C5/2 vein	83/Cii	83/Cii prim.	312/8	312/6
	GRT	AM	GRT	AM	GRT	AM	GRT	AM	GRT	AM
SiO2	38.95	38.27	37.78	38.45	38.89	39.22	38.58	51.20	39.08	38.43
TiO2	0.06	0.31	0.07	0.61	0.04	0.16	0.07	0.04	0.24	0.33
Al2O3	21.61	19.76	20.72	18.25	21.33	18.17	20.95	3.18	19.55	17.82
Cr2O3	0.04	0.06	0.01	0.01	0.06	0.07	0.02	0.00	0.05	0.05
FeO	19.84	14.26	26.32	16.50	23.52	15.18	21.69	12.55	12.60	10.69
MnO	0.64	0.27	1.26	0.29	1.54	0.30	0.48	0.13	0.98	0.12
MgO	8.67	8.74	6.85	8.21	8.16	9.08	4.97	14.87	5.19	12.85
CaO	9.28	10.78	5.98	9.86	6.43	10.21	12.71	12.79	21.72	12.60
Na2O	0.03	3.60	0.03	3.46	0.00	3.52	0.06	0.35	0.01	3.36
K2O	0.01	0.46	0.00	0.28	0.01	0.39	0.00	0.08	0.00	0.58
Total	**99.13**	**96.50**	**99.02**	**95.93**	**99.98**	**96.30**	**99.53**	**95.19**	**99.41**	**96.84**
Si	2.98	5.72	2.96	5.76	2.99	5.84	3.00	7.59	2.98	5.68
Al(iv)	0.02	2.28	0.04	2.24	0.01	2.16	0.00	0.41	0.02	2.32
Al(vi)	1.93	1.20	1.88	0.99	1.92	1.03	1.91	0.14	1.75	0.79
Ti	0.00	0.03	0.00	0.07	0.00	0.02	0.00	0.00	0.01	0.04
Fe'''	0.08	1.00	0.15	1.41	0.09	1.29	0.08	0.14	0.24	0.93
Cr	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01
Fe''	1.19	0.78	1.58	0.66	1.42	0.60	1.33	1.41	0.56	0.40
Mn	0.04	0.03	0.08	0.04	0.10	0.04	0.03	0.02	0.06	0.02
Mg	0.99	1.95	0.80	1.83	0.93	2.02	0.57	3.28	0.59	2.83
Ca	0.76	1.76	0.50	1.63	0.53	1.68	1.06	2.04	1.78	2.04
Na	0.00	1.06	0.00	1.04	0.00	1.04	0.01	0.10	0.00	0.98
K	0.00	0.09	0.00	0.06	0.00	0.08	0.00	0.01	0.00	0.11
X(Ca)	0.26		0.17		0.18		0.35		0.59	
Mg No.	45.42		33.68		39.59		30.21		51.13	
Fe/Mg	1.20	0.40	1.97	0.36	1.53	0.30	2.31	0.43	0.96	0.14
Pyp	**33.20**		**27.01**		**31.26**		**19.21**		**19.71**	
Alm	**39.89**		**53.20**		**47.69**		**44.37**		**18.84**	
Spess	**1.39**		**2.82**		**3.34**		**1.05**		**2.12**	
Gross	**21.19**		**9.35**		**13.13**		**31.03**		**46.52**	
Andr	**4.21**		**7.59**		**4.40**		**4.29**		**12.67**	
Uv	**0.13**		**0.03**		**0.18**		**0.05**		**0.14**	
K(D)	3.00		5.51		5.11		5.38		6.83	
T(C)	767		533		555		696		834	

Table V.iii (cont.)

	Orthopyroxene Eclogite							
	217/ii	217/B	338/2	338/1	338/12	338/14	340/4	340/9
		Grt rim		Grt rim		Grt rim		Grt rim
	GRT	AM	GRT	AM	GRT	AM	GRT	AM
SiO2	39.10	38.49	39.05	44.59	38.54	42.71	38.63	43.56
TiO2	0.06	0.19	0.05	0.67	0.07	0.87	0.02	0.56
Al2O3	21.99	19.50	21.58	12.81	21.46	15.47	21.41	13.84
Cr2O3	0.01	0.00	0.02	0.03	0.06	0.07	0.01	0.02
FeO	20.13	11.83	21.17	11.41	21.33	10.36	23.07	11.20
MnO	0.72	0.08	0.36	0.12	0.53	0.04	0.45	0.04
MgO	8.88	10.35	9.24	12.91	7.04	12.40	7.01	12.80
CaO	8.65	11.78	8.18	11.66	10.16	11.66	9.15	12.30
Na2O	0.02	2.03	0.01	2.12	0.03	2.33	0.02	2.03
K2O	0.01	2.02	0.01	0.25	0.00	0.25	0.01	0.50
Total	**99.56**	**96.27**	**99.66**	**96.56**	**99.21**	**96.15**	**99.78**	**96.84**
Si	2.98	5.75	2.97	6.51	2.97	6.25	2.98	6.38
Al(iv)	0.02	2.25	0.03	1.49	0.03	1.75	0.02	1.62
Al(vi)	1.95	1.19	1.91	0.71	1.93	0.92	1.92	0.77
Ti	0.00	0.02	0.00	0.07	0.00	0.10	0.00	0.06
Fe'''	0.06	0.77	0.11	0.67	0.09	0.63	0.10	0.54
Cr	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Fe''	1.22	0.71	1.23	0.72	1.29	0.64	1.38	0.83
Mn	0.05	0.01	0.02	0.01	0.03	0.00	0.03	0.00
Mg	1.01	2.30	1.05	2.81	0.81	2.70	0.80	2.79
Ca	0.71	1.92	0.67	1.85	0.84	1.85	0.76	1.95
Na	0.00	0.60	0.00	0.61	0.00	0.67	0.00	0.58
K	0.00	0.39	0.00	0.05	0.00	0.05	0.00	0.09
X(Ca)	0.24		0.22		0.28		0.25	
Mg No.	45.27		45.92		38.57		36.76	
Fe/Mg	1.21	0.31	1.18	0.26	1.59	0.24	1.72	0.30
Pyp	**33.84**		**35.26**		**27.22**		**27.06**	
Alm	**40.91**		**41.52**		**43.35**		**46.55**	
Spess	**1.55**		**0.78**		**1.17**		**0.98**	
Gross	**20.35**		**16.65**		**23.59**		**20.28**	
Andr	**3.33**		**5.72**		**4.50**		**5.11**	
Uv	**0.03**		**0.07**		**0.17**		**0.02**	
K(D)	3.93		4.57		6.71		5.77	
T(C)	672		622		586		594	

Table V.iii (cont.)

Western Lewisian Eclogite

	420/1	420/6	420/4	420/8	420/5	420/1	418/4	418/2	417/3	417/3
		vein		prim.		prim.				
	GRT	AM	GRT	AM	GRT	AM	GRT	AM	GRT	AM
SiO2	38.75	39.96	38.27	45.64	38.29	40.54	38.04	39.50	37.89	41.34
TiO2	0.07	0.33	0.03	0.42	0.06	0.28	0.07	0.71	0.08	1.09
Al2O3	21.17	16.73	21.04	9.31	21.11	15.04	20.97	15.51	20.92	13.25
Cr2O3	0.02	0.06	0.00	0.00	0.02	0.04	0.05	0.04	0.01	0.07
FeO	24.06	16.20	25.41	14.18	24.85	17.11	24.26	16.31	25.40	15.16
MnO	0.61	0.09	0.69	0.13	0.53	0.14	0.57	0.10	0.70	0.08
MgO	5.37	8.96	6.42	11.24	5.48	8.66	5.62	8.91	5.51	10.44
CaO	10.49	11.26	7.95	14.13	9.77	11.42	9.65	11.36	8.88	10.53
Na2O	0.02	2.60	0.02	1.76	0.02	2.24	0.06	2.06	0.02	2.65
K2O	0.04	0.95	0.00	0.62	0.00	0.93	0.02	1.35	0.00	1.48
Total	**100.59**	**97.12**	**99.85**	**97.43**	**100.12**	**96.40**	**99.31**	**95.84**	**99.39**	**96.08**
Si	2.99	5.97	2.97	6.93	2.97	6.14	2.97	6.02	2.97	6.24
Al(iv)	0.01	2.03	0.03	1.07	0.03	1.86	0.03	1.98	0.03	1.76
Al(vi)	1.91	0.92	1.90	0.59	1.90	0.83	1.90	0.80	1.90	0.60
Ti	0.00	0.04	0.00	0.05	0.00	0.03	0.00	0.08	0.00	0.12
Fe'''	0.09	0.95	0.13	0.00	0.12	0.85	0.12	0.88	0.13	0.98
Cr	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Fe''	1.46	1.07	1.52	1.80	1.49	1.32	1.46	1.20	1.53	0.94
Mn	0.04	0.01	0.05	0.02	0.04	0.02	0.04	0.01	0.05	0.01
Mg	0.62	2.00	0.74	2.54	0.63	1.95	0.65	2.02	0.64	2.35
Ca	0.87	1.84	0.66	2.27	0.81	1.89	0.81	1.89	0.74	1.74
Na	0.00	0.77	0.00	0.51	0.00	0.67	0.01	0.62	0.00	0.79
K	0.00	0.18	0.00	0.12	0.00	0.18	0.00	0.27	0.00	0.29
X(Ca)	0.29		0.22		0.27		0.27		0.25	
Mg No.	29.65		32.86		29.83		30.86		29.51	
Fe/Mg	2.37	0.54	2.04	0.71	2.35	0.68	2.24	0.59	2.39	0.40
Pyp	**20.65**		**25.04**		**21.33**		**22.06**		**21.64**	
Alm	**49.00**		**51.15**		**50.17**		**49.41**		**51.71**	
Spess	**1.33**		**1.54**		**1.18**		**1.27**		**1.56**	
Gross	**24.34**		**15.71**		**21.09**		**21.00**		**18.51**	
Andr	**4.61**		**6.56**		**6.19**		**6.12**		**6.56**	
Uv	**0.07**		**0.01**		**0.05**		**0.14**		**0.02**	
K(D)	4.41		2.89		3.48		3.78		5.99	
T(C)	690		747		740		716		584	

Table V.iii (cont.)

	Western Lewisian Grt Amphibolite					
	402/A	402/3	446/2	446/3	447/A	447/1
				Grt incl.		Grt incl.
	GRT	AM	GRT	AM	GRT	AM
SiO2	37.84	40.52	37.55	41.32	36.98	42.60
TiO2	0.06	0.70	0.24	0.68	0.16	0.67
Al2O3	20.77	14.66	20.62	14.26	20.52	13.18
Cr2O3	0.03	0.02	0.01	0.00	0.04	0.05
FeO	25.48	17.11	27.17	19.57	23.85	16.75
MnO	1.24	0.36	3.08	0.23	4.71	0.29
MgO	5.80	8.10	1.71	7.13	1.72	8.99
CaO	8.21	11.19	10.11	11.35	11.29	11.42
Na2O	0.04	2.07	0.07	1.92	0.05	2.02
K2O	0.00	1.50	0.01	1.19	0.00	0.84
Total	**99.45**	**96.23**	**100.56**	**97.64**	**99.31**	**96.80**
Si	2.96	6.19	2.98	6.26	2.96	6.41
Al(iv)	0.04	1.81	0.02	1.74	0.04	1.59
Al(vi)	1.88	0.84	1.90	0.81	1.89	0.76
Ti	0.00	0.08	0.01	0.08	0.01	0.08
Fe'''	0.16	0.69	0.09	0.70	0.13	0.62
Cr	0.00	0.00	0.00	0.00	0.00	0.01
Fe''	1.51	1.50	1.71	1.78	1.47	1.49
Mn	0.08	0.05	0.21	0.03	0.32	0.04
Mg	0.68	1.85	0.20	1.61	0.21	2.02
Ca	0.69	1.86	0.86	1.87	0.97	1.87
Na	0.01	0.62	0.01	0.57	0.01	0.60
K	0.00	0.30	0.00	0.23	0.00	0.16
X(Ca)	0.23		0.29		0.33	
Mg No.	30.90		10.54		12.26	
Fe/Mg	2.24	0.81	8.49	1.10	7.15	0.74
Pyp	**22.85**		**6.77**		**6.93**	
Alm	**51.10**		**57.47**		**49.61**	
Spess	**2.79**		**6.95**		**10.77**	
Gross	**15.38**		**23.63**		**25.86**	
Andr	**7.80**		**5.15**		**6.69**	
Uv	**0.08**		**0.03**		**0.13**	
K(D)	2.76		7.69		9.66	
G & P	771		563		549	

Table V.iv : Representative analyses : Am - Pl pairs Blundy & Holland (1990)

Bimineralic Eclogite

	E1/2 sym AM	E1/2 sym PL	E9/4 AM	E9/4 PL	E10/i AM	E10/i PL	264/3 vein AM	264/3 vein PL	353/1 vein AM	353/3 vein PL
SiO2	45.32	63.00	43.23	64.45	43.37	61.35	45.65	65.92	48.86	62.93
TiO2	0.29	0.02	0.40	0.03	0.22	0.02	0.37	0.01	0.61	0.01
Al2O3	10.51	23.10	12.54	21.94	14.64	22.52	11.51	22.30	7.78	23.27
Cr2O3	0.04	0.00	0.03	0.00	0.07	0.02	0.12	0.00	0.00	0.01
FeO	14.11	0.23	10.47	0.16	10.78	0.52	11.44	0.18	9.88	0.07
MnO	0.31	0.02	0.11	0.02	0.12	0.01	0.20	0.01	0.15	0.01
MgO	12.03	0.04	13.89	0.01	12.64	0.37	13.64	0.01	16.08	0.02
CaO	12.05	4.39	12.31	3.37	11.87	5.35	11.54	3.51	12.09	4.63
Na2O	2.27	10.14	2.66	10.22	2.88	9.31	2.62	9.30	1.56	9.45
K2O	0.37	0.06	0.68	0.07	0.14	0.03	0.31	0.05	0.27	0.10
Total	**97.31**	**100.99**	**96.33**	**100.26**	**96.71**	**99.51**	**97.39**	**101.30**	**97.28**	**100.50**
Si	6.70	10.96	6.39	11.31	6.35	10.88	6.62	11.54	6.99	11.05
Al(iv)	1.30		1.61		1.65		1.38		1.01	
Al(vi)	0.53	4.74	0.58	4.54	0.88	4.71	0.59	4.60	0.30	4.82
Ti	0.03	0.00	0.04	0.00	0.02	0.00	0.04	0.00	0.07	0.00
Fe'''	0.17		0.14		0.16		0.32		0.39	
Cr	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00
Fe''	1.58	0.03	1.15	0.02	1.16	0.08	1.07	0.03	0.80	0.01
Mn	0.04	0.00	0.01	0.00	0.02	0.00	0.02	0.00	0.02	0.00
Mg	2.65	0.01	3.06	0.00	2.76	0.10	2.95	0.00	3.43	0.00
Ca	1.92	0.82	1.96	0.63	1.87	1.02	1.81	0.66	1.87	0.87
Na	0.65	3.42	0.77	3.48	0.82	3.20	0.74	3.16	0.44	3.22
K	0.07	0.01	0.13	0.01	0.03	0.01	0.06	0.01	0.05	0.02
Alb.		**0.80**		**0.84**		**0.76**		**0.83**		**0.78**
An.		**0.19**		**0.15**		**0.24**		**0.17**		**0.21**
K - feld		**0.00**		**0.00**		**0.00**		**0.00**		**0.01**
K(D)	**1.67**		**1.26**		**1.08**		**1.56**		**2.32**	
Kb										
10	622		669		697		632		573	
12	593		639		666		603		546	
14	565		609		634		574		518	
16	536		579		603		545		491	
18	507		548		572		516		464	

Table V.iv (cont.)

	Orthopyroxene Eclogite						Quartz Ec.	
	340/7	340/3	340/11	340/4	340/12	340/5	347/E	347/H
	vein	vein					sym	sym
	AM	PL	AM	PL	AM	PL	AM	PL
SiO2	43.25	62.56	44.10	59.41	44.04	60.59	47.43	61.93
TiO2	0.79	0.04	0.95	0.02	0.91	0.03	0.62	0.02
Al2O3	13.18	23.29	12.53	25.49	12.20	24.36	9.83	22.19
Cr2O3	0.00	0.01	0.03	0.01	0.00	0.02	0.12	0.00
FeO	11.24	0.23	11.62	0.22	12.14	0.22	9.95	0.25
MnO	0.04	0.04	0.04	0.01	0.02	0.02	0.06	0.01
MgO	13.03	0.05	12.82	0.00	12.65	0.04	14.61	0.29
CaO	11.90	4.73	11.82	7.27	11.67	6.14	12.30	5.29
Na2O	2.21	9.18	2.09	7.82	2.22	8.31	1.37	8.67
K2O	0.48	0.13	0.48	0.06	0.48	0.05	0.69	0.15
Total	**96.12**	**100.25**	**96.48**	**100.30**	**96.32**	**99.76**	**96.97**	**98.81**
Si	6.37	11.03	6.48	10.54	6.50	10.78	6.87	11.11
Al(iv)	1.63		1.52		1.50		1.13	
Al(vi)	0.66	4.84	0.65	5.33	0.62	5.11	0.55	4.70
Ti	0.09	0.01	0.11	0.00	0.10	0.00	0.07	0.00
Fe'''	0.32		0.25		0.28		0.10	
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Fe''	1.07	0.03	1.18	0.03	1.22	0.03	1.11	0.04
Mn	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.00
Mg	2.86	0.01	2.81	0.00	2.78	0.01	3.15	0.08
Ca	1.89	0.89	1.87	1.38	1.85	1.17	1.91	1.02
Na	0.63	3.14	0.60	2.69	0.64	2.87	0.39	3.02
K	0.09	0.03	0.09	0.01	0.09	0.01	0.13	0.03
Alb.		**0.77**		**0.66**		**0.71**		**0.74**
An.		**0.22**		**0.34**		**0.29**		**0.25**
K - feld		**0.01**		**0.00**		**0.00**		**0.01**
K(D)	**1.13**		**1.07**		**1.18**		**1.89**	
Kb								
10	689		697		681		603	
12	658		666		650		575	
14	627		635		620		547	
16	596		604		589		519	
18	565		573		558		491	

Table V.iv (cont.)

	Eastern Lewisian Amph.				Western Lewisian Eclogite					
	80/3	80/1	510/1	510/1	420/2	420/1	418/5	418/1	417/1	417/1
					sym	sym				
	AM	PL	AM	PL	AM	PL	AM	PL	AM	PL
SiO2	45.15	63.61	41.14	63.20	43.22	64.58	43.24	63.89	41.84	64.85
TiO2	0.52	0.02	0.75	0.01	0.14	0.02	0.12	0.02	1.04	0.03
Al2O3	12.00	23.15	13.40	22.93	11.47	22.44	11.78	21.53	12.16	21.72
Cr2O3	0.01	0.00	0.11	0.00	0.00	0.02	0.02	0.02	0.03	0.00
FeO	15.16	0.14	17.00	0.08	17.37	0.29	15.31	0.44	16.45	0.11
MnO	0.29	0.01	0.23	0.00	0.13	0.00	0.13	0.02	0.10	0.00
MgO	10.69	0.02	9.36	0.03	9.91	0.01	10.93	0.13	9.95	0.00
CaO	11.63	4.43	11.28	3.88	11.66	3.48	11.13	3.31	10.94	3.01
Na2O	1.51	9.97	2.23	10.12	1.84	9.64	2.15	9.65	2.46	10.46
K2O	0.67	0.10	0.98	0.22	0.68	0.08	1.02	0.10	1.24	0.13
Total	**97.62**	**101.45**	**96.47**	**100.48**	**96.42**	**100.55**	**95.82**	**99.11**	**96.21**	**100.31**
Si	6.63	11.04	6.22	11.05	6.51	11.34	6.50	11.38	6.35	11.35
Al(iv)	1.37		1.78		1.49		1.50		1.65	
Al(vi)	0.71	4.74	0.61	4.73	0.55	4.65	0.59	4.52	0.53	4.49
Ti	0.06	0.00	0.09	0.00	0.02	0.00	0.01	0.00	0.12	0.00
Fe'''	0.34		0.49		0.47		0.47		0.36	
Cr	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	1.52	0.02	1.66	0.01	1.72	0.04	1.46	0.07	1.72	0.02
Mn	0.04	0.00	0.03	0.00	0.02	0.00	0.02	0.00	0.01	0.00
Mg	2.34	0.00	2.11	0.01	2.23	0.00	2.45	0.04	2.25	0.00
Ca	1.84	0.82	1.85	0.73	1.90	0.66	1.81	0.63	1.79	0.56
Na	0.43	3.35	0.66	3.43	0.54	3.28	0.63	3.33	0.73	3.55
K	0.13	0.02	0.19	0.05	0.13	0.02	0.20	0.02	0.24	0.03
Alb.		**0.80**		**0.82**		**0.83**		**0.84**		**0.86**
An.		**0.20**		**0.17**		**0.17**		**0.16**		**0.14**
K - feld		**0.01**		**0.01**		**0.00**		**0.01**		**0.01**
K(D)	**1.53**		**1.02**		**1.40**		**1.40**		**1.22**	
Kb										
10	636		707		650		651		674	
12	607		676		621		621		644	
14	578		644		591		592		613	
16	548		613		561		562		583	
18	519		582		532		532		553	

Table V.iv (cont.)

	Western Lewisian Gnt Amph.									
	108/3	108/1	402/1	402/1	402/2	402/2	446/3	446/A	447/3	447/1
	sym	sym								
	AM	PL	AM	PL	AM	PL	AM	PL	AM	PL
SiO2	41.78	64.69	40.85	64.95	40.82	62.76	41.32	64.30	42.45	64.50
TiO2	0.41	0.01	0.73	0.02	0.66	0.01	0.68	0.03	0.68	0.00
Al2O3	15.50	21.89	14.57	22.39	14.54	22.45	14.26	21.73	13.18	21.90
Cr2O3	0.02	0.01	0.05	0.00	0.02	0.00	0.00	0.00	0.06	0.00
FeO	17.23	0.04	17.86	0.22	17.79	0.41	19.57	0.04	16.87	0.07
MnO	0.13	0.02	0.39	0.01	0.40	0.01	0.23	0.01	0.30	0.01
MgO	8.21	0.00	8.21	0.01	8.11	0.02	7.13	0.02	8.86	0.01
CaO	10.70	3.13	11.41	3.20	11.16	4.41	11.35	3.15	11.43	3.38
Na2O	2.22	10.38	2.05	10.75	2.11	10.21	1.92	10.07	2.02	9.94
K2O	0.38	0.07	1.24	0.09	1.40	0.21	1.19	0.13	0.84	0.12
Total	**96.58**	**100.23**	**97.33**	**101.62**	**97.02**	**100.49**	**97.64**	**99.48**	**96.68**	**99.94**
Si	6.23	11.34	6.17	11.20	6.19	10.97	6.26	11.37	6.41	11.37
Al(iv)	1.77		1.83		1.81		1.74		1.59	
Al(vi)	0.96	4.52	0.76	4.56	0.78	4.63	0.81	4.53	0.76	4.55
Ti	0.05	0.00	0.08	0.00	0.08	0.00	0.08	0.00	0.08	0.00
Fe'''	0.58		0.38		0.37		0.31		0.23	
Cr	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Fe''	1.57	0.01	1.88	0.03	1.89	0.06	2.17	0.01	1.90	0.01
Mn	0.02	0.00	0.05	0.00	0.05	0.00	0.03	0.00	0.04	0.00
Mg	1.83	0.00	1.85	0.00	1.83	0.01	1.61	0.00	1.99	0.00
Ca	1.73	0.59	1.86	0.59	1.83	0.83	1.86	0.60	1.86	0.64
Na	0.65	3.53	0.60	3.59	0.62	3.46	0.57	3.45	0.60	3.40
K	0.07	0.01	0.24	0.02	0.27	0.05	0.23	0.03	0.16	0.03
Alb.		**0.85**		**0.85**		**0.80**		**0.85**		**0.84**
An.		**0.14**		**0.14**		**0.19**		**0.15**		**0.16**
K - feld		**0.00**		**0.00**		**0.01**		**0.01**		**0.01**
K(D)	**1.08**		**1.01**		**0.96**		**1.10**		**1.27**	
Kb										
10	696		709		718		693		668	
12	665		677		686		662		638	
14	634		646		655		631		607	
16	603		614		623		600		577	
18	572		583		591		569		547	

Table V.iv (cont.)

Western Lewisian Amphibolites

	258/1	258/2	454/1	454/1	455/2	455/2	449/2	449/1	372/2	372/1
	AM	PL	AM	PL	AM	PL	AM	PL	AM	PL
SiO2	45.96	64.51	45.29	63.57	44.11	63.00	43.11	64.39	43.74	64.53
TiO2	0.42	0.02	0.49	0.01	0.23	0.00	0.67	0.01	0.54	0.03
Al2O3	11.93	23.00	13.89	22.81	14.34	22.92	12.89	22.48	10.78	21.76
Cr2O3	0.07	0.02	0.03	0.00	0.01	0.00	0.00	0.01	0.05	0.02
FeO	12.34	0.10	9.82	0.04	10.31	0.05	15.90	0.04	15.16	0.08
MnO	0.27	0.01	0.19	0.00	0.21	0.00	0.30	0.00	0.35	0.01
MgO	12.63	0.01	13.49	0.01	12.93	0.03	9.86	0.02	11.34	0.02
CaO	11.70	3.80	11.61	4.42	11.48	4.72	11.18	3.30	11.72	3.30
Na2O	1.77	10.53	2.17	9.90	2.25	9.31	2.10	10.59	1.63	10.02
K2O	0.48	0.08	0.77	0.09	0.76	0.07	1.06	0.16	0.96	0.10
Total	**97.57**	**102.07**	**97.75**	**100.86**	**96.62**	**100.08**	**97.07**	**100.99**	**96.25**	**99.85**
Si	6.66	11.09	6.50	11.10	6.42	11.12	6.44	11.17	6.55	11.38
Al(iv)	1.34		1.50		1.58		1.56		1.45	
Al(vi)	0.69	4.66	0.85	4.70	0.89	4.77	0.71	4.60	0.46	4.53
Ti	0.05	0.00	0.05	0.00	0.02	0.00	0.07	0.00	0.06	0.00
Fe'''	0.34		0.22		0.28		0.32		0.45	
Cr	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Fe''	1.15	0.01	0.96	0.01	0.97	0.01	1.66	0.01	1.45	0.01
Mn	0.03	0.00	0.02	0.00	0.03	0.00	0.04	0.00	0.04	0.00
Mg	2.73	0.00	2.89	0.00	2.81	0.01	2.19	0.00	2.53	0.00
Ca	1.83	0.70	1.79	0.83	1.80	0.89	1.80	0.61	1.90	0.62
Na	0.50	3.51	0.61	3.35	0.64	3.19	0.61	3.56	0.48	3.43
K	0.09	0.02	0.14	0.02	0.14	0.01	0.20	0.04	0.18	0.02
Alb.		**0.83**		**0.80**		**0.78**		**0.85**		**0.84**
An.		**0.17**		**0.20**		**0.22**		**0.15**		**0.15**
K - feld		**0.00**		**0.00**		**0.00**		**0.01**		**0.01**
K(D)	**1.64**		**1.33**		**1.20**		**1.32**		**1.48**	
Kb										
10	625		659		678		661		641	
12	596		629		647		631		612	
14	567		599		617		601		582	
16	538		569		586		571		553	
18	509		539		556		541		524	

Table V.v : Representative analyses : Grt - Pl pairs Koziol & Newton (1988)

	Quartz Eclogite						Marble Nod.	
	83/Cii	83/Cii	347/C	347/2	351/B/1	351/1	260/8	260/11
	GRT	PL	GRT	PL	GRT	PL	GRT	PL
SiO2	38.58	62.13	38.76	63.49	38.09	63.73	36.70	68.32
TiO2	0.07	0.01	0.05	0.01	0.06	0.01	0.04	0.01
Al2O3	20.95	23.57	21.80	22.29	21.31	21.94	20.07	19.21
Cr2O3	0.02	0.01	0.00	0.01	0.01	0.00	0.03	0.00
FeO	21.69	0.33	20.62	0.06	23.40	0.08	35.03	0.06
MnO	0.48	0.00	0.33	0.02	0.31	0.00	0.85	0.00
MgO	4.97	0.03	7.48	0.01	6.60	0.02	4.39	0.03
CaO	12.71	5.32	10.77	4.02	9.45	3.60	2.02	0.26
Na2O	0.06	9.48	0.02	9.64	0.01	9.79	0.02	11.16
K2O	0.00	0.07	0.01	0.26	0.01	0.08	0.01	0.08
Total	**99.53**	**100.93**	**99.83**	**99.81**	**99.24**	**99.24**	**99.15**	**99.12**
Si	3.00	5.43	2.96	5.61	2.96	5.66	2.96	6.04
Al(iv)	0.00		0.04		0.04		0.04	
Al(vi)	1.91	2.43	1.92	2.32	1.91	2.30	1.87	2.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe'''	0.08		0.11		0.13		0.16	
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	1.33	0.02	1.20	0.00	1.39	0.01	2.20	0.00
Mn	0.03	0.00	0.02	0.00	0.02	0.00	0.06	0.00
Mg	0.57	0.00	0.85	0.00	0.76	0.00	0.53	0.00
Ca	1.06	0.50	0.88	0.38	0.79	0.34	0.17	0.02
Na	0.01	1.61	0.00	1.65	0.00	1.68	0.00	1.91
K	0.00	0.01	0.00	0.03	0.00	0.01	0.00	0.01
X(Ca)	0.35		0.30		0.27		0.06	
Mg No.	30.21		41.40		35.50		19.36	
Pyp/Alb	**19.21**	**0.76**	**28.77**	**0.80**	**25.82**	**0.83**	**17.83**	**0.98**
Alm/An	**44.37**	**0.24**	**40.72**	**0.18**	**46.92**	**0.17**	**74.30**	**0.01**
Sps/Kf	**1.05**	**0.00**	**0.71**	**0.01**	**0.68**	**0.00**	**1.96**	**0.00**
Gross	**31.03**		**24.15**		**19.94**		**0.00**	
And	**4.29**		**5.65**		**6.63**		**8.19**	
Uv	**0.05**		**0.00**		**0.02**		**0.08**	
a(Pl)3/a(gt)	-0.33		-0.26		-0.26		-0.01	
at 750C : (from Essene, 1989)	17 Kb		17 Kb		17 Kb		16 Kb	

Table V.vi : Representative analyses : Spn - Pl Manning & Bohlen (1991)

	Bimin. Ec.		Quartz Eclogite			
	E2/A/2	E2/A/1	83/1	83/C	347/1	347/2
	SPH	PL	SPH	PL	SPH	PL
SiO2	30.30	59.41	30.05	61.44	29.86	63.47
TiO2	37.07	0.01	36.18	0.02	34.82	0.12
Al2O3	2.31	25.54	2.43	24.53	3.40	22.93
Cr2O3	0.02	0.01	0.01	0.01	0.00	0.01
FeO	0.25	0.04	0.55	0.06	0.43	0.13
MnO	0.02	0.00	0.01	0.00	0.03	0.00
MgO	0.02	0.01	0.03	0.01	0.04	0.02
CaO	29.01	7.32	28.45	5.64	28.41	4.48
Na2O	0.02	7.57	0.00	9.02	0.02	9.14
K2O	0.01	0.05	0.01	0.10	0.02	0.11
Total	**99.04**	**99.96**	**97.70**	**100.83**	**97.04**	**100.40**
Si	3.94	10.59	3.96	10.77	3.94	11.19
Al	0.35	5.37	0.38	5.07	0.53	4.77
Ti	3.63	0.00	3.58	0.00	3.46	0.02
Cr	0.00	0.00	0.00	0.00	0.00	0.00
Fe''' or Fe''	0.03	0.01	0.07	0.01	0.05	0.02
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.00	0.00	0.01	0.00	0.01	0.00
Ca	4.04	1.40	4.01	1.06	4.02	0.85
Na	0.01	2.62	0.00	3.07	0.01	3.13
K	0.00	0.01	0.00	0.02	0.00	0.02
Total	12.00	20.00	12.01	20.00	12.01	20.00
Albite		**0.65**	1.00	**0.74**	1.00	**0.78**
Anorth.		**0.35**	0.90	**0.26**	0.86	**0.21**
K - feld		**0.00**	0.99	**0.01**	0.98	**0.01**
ln K(D)	-0.33		-0.45		-0.50	

at 750 C : 16 Kb 17 Kb 17.5 Kb
(from Manning & Bohlen, 1991)

Table V.vii : Representative analyses : Grt - Pl - Am Kohn & Spear (1990)

& T from Blundy & Holland (1990) and Graham and Powell (1984)

	W.L. Eclogite			Western Lewisian Grt Amph.					
	417/4	417/1	417/1	447/B	447/A	447/A	108A/1	108A/1	108A/1
	GNT	AM	PL	GNT	AM	PL	GNT	AM	PL
SiO2	37.81	41.84	64.85	37.12	42.26	63.79	36.95	41.85	64.69
TiO2	0.06	1.04	0.03	0.10	0.63	0.03	0.05	0.43	0.01
Al2O3	20.82	12.16	21.72	20.73	13.24	22.39	20.26	14.85	21.89
Cr2O3	0.02	0.03	0.00	0.04	0.08	0.00	0.04	0.03	0.01
FeO	24.98	16.45	0.11	23.24	17.11	0.26	29.08	17.60	0.04
MnO	0.67	0.10	0.00	4.02	0.29	0.01	2.28	0.15	0.02
MgO	5.02	9.95	0.00	1.84	8.93	0.01	2.24	8.21	0.00
CaO	9.65	10.94	3.01	12.18	11.31	3.82	8.32	10.74	3.13
Na2O	0.02	2.46	10.46	0.03	1.94	9.79	0.02	2.21	10.38
K2O	0.00	1.24	0.13	0.00	0.80	0.10	0.00	0.35	0.07
Total	**99.03**	**96.21**	**100.31**	**99.30**	**96.58**	**100.20**	**99.23**	**96.41**	**100.23**
Si	2.97	6.35	11.35	2.96	6.37	11.22	2.97	6.27	11.34
Al(iv)	0.03	1.65		0.04	1.63		0.03	1.73	
Al(vi)	1.90	0.53	4.49	1.91	0.72	4.65	1.90	0.89	4.52
Ti	0.00	0.12	0.00	0.01	0.07	0.00	0.00	0.05	0.00
Fe'''	0.12	0.36		0.12	0.39		0.12	0.59	
Cr	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Fe''	1.53	1.72	0.02	1.43	1.77	0.04	1.83	1.62	0.01
Mn	0.04	0.01	0.00	0.27	0.04	0.00	0.16	0.02	0.00
Mg	0.59	2.25	0.00	0.22	2.00	0.00	0.27	1.83	0.00
Ca	0.81	1.79	0.56	1.04	1.84	0.72	0.72	1.75	0.59
Na	0.00	0.73	3.55	0.00	0.57	3.34	0.00	0.65	3.53
K	0.00	0.24	0.03	0.00	0.15	0.02	0.00	0.07	0.01
X(Ca)	0.27			0.35			0.24		
Mg No.	27.83	56.60		13.28	53.15		12.76	53.15	
Fe/Mg	2.59	0.77		6.53	0.88		6.84	0.88	
Pyp/Alb.	**19.80**		**0.86**	**7.40**		**0.82**	**9.01**		**0.85**
Alm/An.	**51.35**		**0.14**	**48.30**		**0.18**	**61.64**		**0.14**
Sps/Kf.	**1.51**		**0.01**	**9.17**		**0.01**	**5.22**		**0.00**
Gross.	**21.42**			**28.85**			**17.73**		
And.	**5.88**			**6.16**			**6.29**		
Uv.	**0.05**			**0.12**			**0.12**		
K(D) - Mg	911.27			36.31			28.12		
K(D) - Fe	18440.52			5423.53			6592.89		
P(Mg)	**14.75** [700C]			**11.80** [600C]			**11.61** [600C]		
P(Fe)	**14.06** [700C]			**12.09** [600C]			**12.22** [600C]		
K(D) - [B&H]	**1.22**			**1.19**			**1.12**		
Pl - Am (B & H)									
10	674			679			690		
12	644			648			659		
14	613			618			628		
16	583			587			597		
18	553			557			566		
K(D) - [G&P]	**3.38**			**7.41**			**7.76**		
T(C) : G & P	749			620			524		

APPENDIX VI

Fe''' calculation and its effect on mineral compositions

Fe''' contents have been calculated in garnet, clinopyroxene, amphibole and biotite using the method of Droop (1987) and by charge balance ('charge' in the following tables). For garnet and clinopyroxene Fe''' is also calculated by the method of Ryburn *et al.* (1976), whilst for clinopyroxene it is also calculated by assuming that Fe''' = Na - Al_{vi}, i.e. that there may be aegerine, but no ferritschermak's molecule, and also by assuming that Fe''' = Na + Al_{iv} + K - Ti - Al_{vi} - Cr, i.e. that charge is balanced for all substitutions other than $Ca(Mg,Fe)Si_2O_6$ ('Stoich' in the following tables).

Analyses calculated by these various methods are presented below. Table VI.i is for two garnets, one comparatively Ca - rich, Fe - poor, the other Ca - poor, Fe - rich. Table VI.ii is for two clinopyroxenes, one in which Al_{vi} > Na, and one in which Al_{vi} < Na. Table VI.iii is for two amphiboles, one Na, Al rich, one Si rich, and for a biotite. In chapter five it was shown that if Na > Al_{vi} then it is difficult to calculate jadeite contents accurately, affecting pressure calculations.

All methods of Fe''' calculation give roughly similar compositions for garnet, clinopyroxene and amphibole, except for the method used for clinopyroxenes where the assumption is made that Fe''' = Na - Al_{vi}. The methods of charge balance and after Droop (1987) give very different results for biotites.

The calculation of Fe''' contents is most important in thermobarometry using Fe - Mg exchange thermometers. Changes in the estimated Fe''' content will affect clinopyroxene most of all due to the low overall Fe content. Table Vi.iv and Vi.v give garnet - clinopyroxene themometers with Fe''' content calculated in each of the above ways for a clinopyroxene where Al_{vi} > Na and Al_{vi} < Na respectively. Table VI.vi is for a garnet - biotite pair.

Given that for most minerals different methods of calculation of Fe''' content give reasonably similar results, throughout this thesis Fe''' in garnet and clinopyroxene is calculated after Ryburn et al. (1976), whilst Fe''' content of amphibole and biotite is calculated after Droop (1987) using the assumptions of Essene (1989).

Fe''' contents of some published mineral analyses used in estimating conditions of metamorphism by Sanders (1988, 1989) are re - calculated using the above methods, and new temperatures of metamorphism obtained using Krogh (1988) for garnet - clinopyroxene pairs and Indares and Martignole (1985) for one garnet - biotite pair. The temperatures obtained are higher than those published by Sanders (1988, 1989) and consist~~a~~ent with the temperatures given in appendix V for my own analyses. These are summarised in table VI.viii.

Table VI.i : Fe''' in Grt

	E2/B/1 Ryburn	E2/B/1 Charge	E2/B/1 Droop	C1/I Ryburn	C1/I Charge	C1/I Droop
SiO2	38.76	38.76	38.76	37.30	37.30	37.30
TiO2	0.05	0.05	0.05	0.01	0.01	0.01
Al2O3	21.64	21.64	21.64	20.95	20.95	20.95
Cr2O3	0.03	0.03	0.03	0.03	0.03	0.03
FeO	20.39	20.39	20.39	29.97	29.97	29.97
MnO	0.69	0.69	0.69	2.77	2.77	2.77
MgO	8.02	8.02	8.02	4.65	4.65	4.65
CaO	10.09	10.09	10.09	4.04	4.04	4.04
Na2O	0.06	0.06	0.06	0.03	0.03	0.03
K2O	0.01	0.01	0.01	0.00	0.00	0.00
Total	**99.73**	**99.73**	**99.73**	**99.75**	**99.75**	**99.75**
Si	2.96	2.96	2.96	2.96	2.96	2.96
Al(iv)	0.04	0.04	0.04	0.04	0.04	0.04
Al(vi)	1.90	1.90	1.90	1.92	1.92	1.92
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Fe'''	0.13	0.14	0.14	0.11	0.12	0.12
Cr	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	1.17	1.16	1.16	1.88	1.87	1.87
Mn	0.04	0.04	0.04	0.19	0.19	0.19
Mg	0.91	0.91	0.91	0.55	0.55	0.55
Ca	0.82	0.82	0.82	0.34	0.34	0.34
Na	0.01	0.01	0.01	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00
X(Ca)	27.94	28.03	28.06	11.62	11.64	11.65
Mg No.	43.82	44.02	44.08	22.65	22.69	22.71
Fe'''/Fe''	0.11	0.12	0.12	0.06	0.06	0.06
Fe''/Mg	1.28	1.27	1.27	3.42	3.41	3.40
Pyrope	**30.92**	**31.02**	**31.05**	**18.59**	**18.62**	**18.63**
Almand.	**39.64**	**39.44**	**39.38**	**63.50**	**63.45**	**63.41**
Spess.	**1.50**	**1.51**	**1.51**	**6.29**	**6.30**	**6.31**
Gross.	**21.27**	**20.93**	**20.83**	**5.98**	**5.81**	**5.68**
Andr.	**6.59**	**7.02**	**7.15**	**5.53**	**5.72**	**5.86**
Uvarav.	**0.09**	**0.09**	**0.09**	**0.10**	**0.10**	**0.10**

Table VI.ii : Fe''' in Cpx

	E2/6 Ryburn	E2/6 Charge	E2/6 Droop	E2/6 Na - Al	E2/6 Stoich	E10/IPi Ryburn	E10/IPi Charge	E10/IPi Droop	E10/IPi Na - Al	E10/IPi Stoich
SiO2	52.40	52.40	52.40	52.40	52.40	53.57	53.57	53.57	53.57	53.57
TiO2	0.34	0.34	0.34	0.34	0.34	0.28	0.28	0.28	0.28	0.28
Al2O3	6.98	6.98	6.98	6.98	6.98	8.18	8.18	8.18	8.18	8.18
Cr2O3	0.12	0.12	0.12	0.12	0.12	0.08	0.08	0.08	0.08	0.08
FeO	4.57	4.57	4.57	4.57	4.57	4.87	4.87	4.87	4.87	4.87
MnO	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06
MgO	11.97	11.97	11.97	11.97	11.97	10.36	10.36	10.36	10.36	10.36
CaO	20.64	20.64	20.64	20.64	20.64	17.56	17.56	17.56	17.56	17.56
Na2O	2.59	2.59	2.59	2.59	2.59	4.47	4.47	4.47	4.47	4.47
K2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	**99.67**	**99.67**	**99.67**	**99.67**	**99.67**	**99.43**	**99.43**	**99.43**	**99.43**	**99.43**
Si	1.91	1.91	1.91	1.91	1.91	1.94	1.94	1.94	1.94	1.94
Al(iv)	0.09	0.09	0.09	0.09	0.09	0.06	0.06	0.06	0.06	0.06
Al(vi)	0.21	0.21	0.21	0.21	0.21	0.29	0.29	0.29	0.29	0.29
Ti	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Fe'''	0.04	0.03	0.04	0.00	0.05	0.07	0.06	0.07	0.03	0.08
Cr	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	0.09	0.11	0.09	0.14	0.09	0.08	0.08	0.08	0.12	0.07
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.65	0.65	0.65	0.65	0.65	0.56	0.56	0.56	0.56	0.56
Ca	0.81	0.81	0.81	0.81	0.81	0.68	0.68	0.68	0.68	0.68
Na	0.18	0.18	0.18	0.18	0.18	0.31	0.31	0.31	0.31	0.31
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na No.	18.48	18.48	18.48	18.48	18.48	31.53	31.53	31.53	31.53	31.53
Mg No.	87.26	86.08	87.31	82.36	88.37	87.93	86.95	88.00	82.18	88.98
Fe'''/Fe''	0.47	0.32	0.47	0.00	0.63	0.92	0.76	0.93	0.22	1.13
Fe''/Mg	0.15	0.16	0.15	0.21	0.13	0.14	0.15	0.14	0.22	0.12
Jadeite	**18.26**	**18.26**	**18.26**	**18.26**	**18.26**	**28.74**	**28.74**	**28.74**	**28.74**	**28.74**
Aegerine	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**2.64**	**2.64**	**2.64**	**2.64**	**2.64**
Tsch.	**8.63**	**8.12**	**8.56**	**6.43**	**9.11**	**5.80**	**5.56**	**5.94**	**3.58**	**6.18**
Heden.	**9.71**	**10.73**	**9.66**	**14.14**	**8.77**	**7.85**	**8.56**	**7.80**	**12.30**	**7.10**
Diopside	**63.41**	**62.90**	**63.52**	**61.17**	**63.86**	**54.97**	**54.49**	**54.87**	**52.74**	**55.34**

Table VI.iii : Fe'' in Amph & Bt

	E5/3 Charge	E5/3 Droop	511/2 Charge	511/2 Droop
SiO2	42.34	42.34	54.28	54.28
TiO2	0.57	0.57	0.10	0.10
Al2O3	15.23	15.23	2.73	2.73
Cr2O3	0.09	0.09	0.10	0.10
FeO	11.27	11.27	7.10	7.10
MnO	0.09	0.09	0.12	0.12
MgO	12.85	12.85	18.83	18.83
CaO	10.95	10.95	13.17	13.17
Na2O	3.38	3.38	0.35	0.35
K2O	0.39	0.39	0.04	0.04
Total	**97.14**	**97.14**	**96.82**	**96.82**
Si	6.15	6.15	7.69	7.69
Al(iv)	1.85	1.85	0.31	0.31
Al(vi)	0.76	0.76	0.15	0.15
Ti	0.06	0.06	0.01	0.01
Fe'''	0.48	0.52	0.04	0.03
Cr	0.01	0.01	0.01	0.01
Fe''	0.89	0.85	0.80	0.81
Mn	0.01	0.01	0.01	0.01
Mg	2.78	2.78	3.98	3.98
Ca	1.72	1.72	2.00	2.00
Na	0.96	0.96	0.10	0.10
K	0.07	0.07	0.01	0.01
Na No.	34.88	34.88	4.61	4.61
Mg No.	75.74	76.63	83.21	83.04
Fe'''/Fe''	0.54	0.61	0.05	0.04
Fe''/Mg	0.32	0.30	0.20	0.20

	E2/3 Zero	E2/3 Droop	E2/3 Charge	E2/3 15%
SiO2	37.68	37.68	37.68	37.68
TiO2	3.23	3.23	3.23	3.23
Al2O3	15.51	15.51	15.51	15.51
Cr2O3	0.04	0.04	0.04	0.04
FeO	11.84	11.84	11.84	11.84
MnO	0.09	0.09	0.09	0.09
MgO	16.42	16.42	16.42	16.42
CaO	0.02	0.02	0.02	0.02
Na2O	0.17	0.17	0.17	0.17
K2O	9.40	9.40	9.40	9.40
Total	**94.41**	**94.41**	**94.41**	**94.41**
Si	5.68	5.68	5.68	5.68
Al(iv)	2.32	2.32	2.32	2.32
Al(vi)	0.44	0.44	0.44	0.44
Ti	0.37	0.37	0.37	0.37
Fe'''	0.00	0.09	1.15	0.22
Cr	0.01	0.01	0.01	0.01
Fe''	1.49	1.40	0.35	1.27
Mn	0.01	0.01	0.01	0.01
Mg	3.69	3.69	3.69	3.69
Ca	0.00	0.00	0.00	0.00
Na	0.05	0.05	0.05	0.05
K	1.94	1.94	1.94	1.94
Mg No.	0.71	0.73	0.91	0.74
Fe''/Mg	0.40	0.38	0.09	0.34

TABLE VI.iv : Fe''' & t. calc for Grt & Cpx.

(where Al(vi) < Na)

Wt% Oxide	353/5	353/1	353/1	353/1	353/1	353/1	353/1
	Ryburn	Ryburn	Zero (!)	Na - Al(vi)	Stoich	Droop	charge
	GNT	CPX	CPX	CPX	CPX	CPX	CPX
SiO2	39.14	53.79	53.79	53.79	53.79	53.79	53.79
TiO2	0.04	0.26	0.26	0.26	0.26	0.26	0.26
Al2O3	21.16	8.67	8.67	8.67	8.67	8.67	8.67
Cr2O3	0.03	0.07	0.07	0.07	0.07	0.07	0.07
FeO	20.65	4.83	4.83	4.83	4.83	4.83	4.83
MnO	0.44	0.04	0.04	0.04	0.04	0.04	0.04
MgO	8.80	10.27	10.27	10.27	10.27	10.27	10.27
CaO	8.88	16.87	16.87	16.87	16.87	16.87	16.87
Na2O	0.04	4.86	4.86	4.86	4.86	4.86	4.86
K2O	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total	**99.18**	**99.67**	**99.67**	**99.67**	**99.67**	**99.67**	**99.67**
Form. Unit	4.62	2.18	2.18	2.18	2.18	2.18	2.18
Total	8.03	4.03	4.03	4.03	4.03	4.03	4.03
Si	3.00	1.94	1.94	1.94	1.94	1.94	1.94
Al(iv)	0.00	0.06	0.06	0.06	0.06	0.06	0.06
Al(vi)	1.91	0.30	0.30	0.30	0.30	0.30	0.30
Ti	0.00	0.01	0.01	0.01	0.01	0.01	0.01
Fe'''	0.09	0.08	0.00	0.04	0.08	0.08	0.09
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''	1.23	0.06	0.15	0.11	0.06	0.06	0.05
Mn	0.03	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.00	0.55	0.55	0.55	0.55	0.55	0.55
Ca	0.73	0.65	0.65	0.65	0.65	0.65	0.65
Na	0.01	0.34	0.34	0.34	0.34	0.34	0.34
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	8.00	4.00	4.00	4.00	4.00	4.00	4.00
X(Ca)	0.24						
Mg No.	44.92	89.99	79.12	83.37	89.99	90.07	91.03
Fe'''/Fe''(%)	7.40	137.20	0.00	32.31	137.20	139.37	167.71
Fe/Mg	1.23	0.11	0.26	0.20	0.11	0.11	0.10
Z	3.00	2.00	2.00	2.00	2.00	2.00	2.00
Y	2.00	1.01	1.01	1.01	1.01	1.01	1.01
X	2.99	0.99	0.99	0.99	0.99	0.99	0.99
Pyp/Jad	**33.56**	**30.38**	**30.38**	**30.38**	**30.38**	**30.38**	**30.38**
Alm/Aeg	**41.15**	**3.55**	**0.00**	**3.55**	**3.55**	**3.55**	**3.55**
Spess/Tsch	**0.95**	**6.10**	**3.67**	**3.67**	**6.10**	**6.12**	**6.45**
Gross	**19.60**						
And/Heden	**4.65**	**6.25**	**14.65**	**11.11**	**6.25**	**6.19**	**5.55**
Uv/Diop	**0.10**	**53.72**	**51.30**	**51.30**	**53.72**	**53.75**	**54.07**
K(D)		11.02	4.65	6.15	11.02	11.12	12.44
ln K(D)		2.40	1.54	1.82	2.40	2.41	2.52
Temp.	(C)	(Krogh, 1988)					
Pressure	(Kb)						
10		632	859	774	632	630	607
12		637	865	780	637	635	612
14		642	872	786	642	640	617
16		647	878	791	647	645	622
18		652	884	797	652	650	627
X(Jd)		0.30	0.30	0.30	0.30	0.30	0.30
1-X(Jd)		0.70	0.70	0.70	0.70	0.70	0.70
P (Kb) - Cpx		13.59	17.21	15.85	13.59	13.56	13.21
		E&G	E&G	E&G	E&G	E&G	E&G
T (C) - Cpx		640	880	790	640	638	615
T (K) - Cpx		913.15	1153.15	1063.15	913.15	911.15	888.15

TABLE VI.v : Fe''' & t. calc for Grt & Cpx.

(where Al(vi) > Na)

Wt% Oxide		E2/5	E2/6	E2/6	E2/6	E2/6	E2/6	E2/6
		Ryburn	Ryburn	Zero (!)	Na - Al(vi)	Stoich	Droop	charge
		GNT	CPX	CPX	CPX	CPX	CPX	CPX
SiO2		38.89	52.45	52.45	52.45	52.45	52.45	52.45
TiO2		0.05	0.36	0.36	0.36	0.36	0.36	0.36
Al2O3		21.64	9.33	9.33	9.33	9.33	9.33	9.33
Cr2O3		0.03	0.03	0.03	0.03	0.03	0.03	0.03
FeO		20.82	4.90	4.90	4.90	4.90	4.90	4.90
MnO		0.85	0.08	0.08	0.08	0.08	0.08	0.08
MgO		7.57	10.36	10.36	10.36	10.36	10.36	10.36
CaO		10.03	18.19	18.19	18.19	18.19	18.19	18.19
Na2O		0.03	3.82	3.82	3.82	3.82	3.82	3.82
K2O		0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total		**99.91**	**99.50**	**99.50**	**99.50**	**99.50**	**99.50**	**99.50**
Form. Unit		4.61	2.19	2.19	2.19	2.19	2.19	2.19
Total		8.04	4.01	4.01	4.01	4.01	4.01	4.01
Si		2.97	1.90	1.90	1.90	1.90	1.90	1.90
Al(iv)		0.03	0.10	0.10	0.10	0.10	0.10	0.10
Al(vi)		1.92	0.30	0.30	0.30	0.30	0.30	0.30
Ti		0.00	0.01	0.01	0.01	0.01	0.01	0.01
Fe'''		0.10	0.04	0.00	0.00	0.04	0.04	0.05
Cr		0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe''		1.23	0.11	0.15	0.15	0.11	0.11	0.10
Mn		0.06	0.00	0.00	0.00	0.00	0.00	0.00
Mg		0.86	0.56	0.56	0.56	0.56	0.56	0.56
Ca		0.82	0.71	0.71	0.71	0.71	0.71	0.71
Na		0.00	0.27	0.27	0.27	0.27	0.27	0.27
K		0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total		8.00	4.00	4.00	4.00	4.00	4.00	4.00
X(Ca)		0.28						
Mg No.		41.14	84.04	79.01	79.01	84.04	84.12	85.31
Fe'''/Fe''(%)		7.91	39.88	0.00	0.00	39.88	40.67	54.20
Fe/Mg		1.43	0.19	0.27	0.27	0.19	0.19	0.17
Z		3.00	2.00	2.00	2.00	2.00	2.00	2.00
Y		2.03	1.02	1.02	1.02	1.02	1.02	1.02
X		2.97	0.98	0.98	0.98	0.98	0.98	0.98
Pyp/Jad		**29.01**	**26.84**	**26.84**	**26.84**	**26.84**	**26.84**	**26.84**
Alm/Aeg		**41.50**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Spess/Tsch		**1.85**	**9.19**	**7.07**	**7.07**	**9.19**	**9.22**	**9.69**
Gross		**22.57**						
And/Heden		**4.96**	**10.87**	**15.12**	**15.12**	**10.87**	**10.81**	**9.89**
Uv/Diop		**0.10**	**53.09**	**50.97**	**50.97**	**53.09**	**53.12**	**53.58**
K(D)			7.53	5.39	5.39	7.53	7.58	8.31
ln K(D)			2.02	1.68	1.68	2.02	2.03	2.12
Temp.	(C)		(Krogh, 1988)					
Pressure	(Kb)							
10			746	841	841	746	744	721
12			751	847	847	751	750	726
14			757	853	853	757	755	732
16			762	859	859	762	761	737
18			768	865	865	768	766	743
X(Jd)			0.27	0.27	0.27	0.27	0.27	0.27
1-X(Jd)			0.73	0.73	0.73	0.73	0.73	0.73
P (Kb) - Cpx			14.84	16.27	16.27	14.84	14.83	14.51
			E&G	E&G	E&G	E&G	E&G	E&G
T (C) - Cpx			758	861	861	758	757	734
T (K) - Cpx			1031.15	1134.15	1134.15	1031.15	1030.15	1007.15

TABLE VI.vi : Fe''' & T. calc for Grt & Bt

	E2/8	E2/1	E2/1	E2/1	E2/1
	GNT	BIOT	BIOT	BIOT	BIOT
	Ryburn	Zero	Droop	Stoich	Fe''' = 15%
SiO2	38.84	37.15	37.15	37.15	37.15
TiO2	0.08	3.20	3.20	3.20	3.20
Al2O3	21.50	15.78	15.78	15.78	15.78
Cr2O3	0.05	0.05	0.05	0.05	0.05
FeO	20.36	12.34	12.34	12.34	12.34
MnO	0.64	0.15	0.15	0.15	0.15
MgO	8.28	16.04	16.04	16.04	16.04
CaO	9.99	0.01	0.01	0.01	0.01
Na2O	0.04	0.17	0.17	0.17	0.17
K2O	0.00	8.81	8.81	8.81	8.81
Total	**99.80**	**93.70**	**93.70**	**93.70**	**93.70**
Form. Unit	4.61	9.80	9.80	9.80	9.80
Total	8.05	15.09	15.09	15.09	15.09
Si	2.96	5.62	5.62	5.62	5.62
Al(iv)	0.04	2.38	2.38	2.38	2.38
Al(vi)	1.89	0.43	0.43	0.43	0.43
Ti	0.00	0.36	0.36	0.36	0.36
Fe'''	0.14	0.00	0.27	1.10	0.25
Cr	0.00	0.01	0.01	0.01	0.01
Fe''	1.16	1.56	1.29	0.46	1.33
Mn	0.04	0.02	0.02	0.02	0.02
Mg	0.94	3.62	3.62	3.62	3.62
Ca	0.82	0.00	0.00	0.00	0.00
Na	0.01	0.05	0.05	0.05	0.05
K	0.00	1.83	1.83	1.83	1.83
Total	8.00	14.00	14.00	14.00	14.02
X(Ca)	0.28	X(Al)	X(Al)	X(Al)	X(Al)
Mg No.	44.78	0.07	0.08	0.09	0.08
Fe'''/Fe''(%)	11.85	X(Ti)	X(Ti)	X(Ti)	X(Ti)
		0.06	0.06	0.07	0.06
Fe/Mg	1.23	0.43	0.36	0.13	0.37
Z	3.00				
Y	2.04				
X	2.96				
Pyp	**31.81**				
Alm	**39.22**				
Spess	**1.39**				
Gross	**20.45**				
And	**6.99**				
Uv	**0.15**				
X(Mn)	0.01				
K(D)		0.35015506	0.2889745	0.10330701	0.2976318
ln K(D)		-1.04937918	-1.24141683	-2.27005	-1.21189811

Temp. (C)	Indares & Martignole (1985)			
Pressure (Kb)				
10	798	716	458	727
12	809	725	464	737
14	819	735	471	747
16	830	744	477	756
18	840	754	483	766

TABLE VI.vii : Recalculation of published analyses (Sanders 1988, 1989)

	(1989)			(1988)				(1989) - opx ec.	
	S215	S215		32gar1	32cpx1	32gar2	32cpx2	460	460
Wt%Oxide				Host	Host	Streak	Streak		
	GRT	CPX		GRT	CPX	GRT	CPX	GRT	BT
SiO2	39.02	53.76	Si	2.98	1.99	3.02	1.92		
TiO2		0.28	Al(vi)	2.00	0.25	1.99	0.58		
Al2O3	22.02	7.65		0.00	0.01	0.00	0.01		
Cr2O3			Fe'''	0.00	0.00	0.00	0.00		
FeO	22.12	5.63	Fe''	1.47	0.19	1.24	0.12		
MnO	0.64	0.06	Mn	0.03	0.00	0.02	0.00		
MgO	8.41	10.39	Mg	1.01	0.58	0.62	0.41		
CaO	7.78	17.15	Ca	0.53	0.73	1.11	0.53		
Na2O		4.45	Na	0.00	0.27	0.00	0.44		
K2O		0.01		0.00	0.00	0.00	0.00		
Total	**99.99**	**99.38**							
Recalculated Fe''' after Ryburn et al. (1976)									
Si	2.98	1.95		2.97	1.98	3.02	1.92	1.00	5.69
Al(iv)	0.02	0.05		0.03	0.02	0.00	0.08	0.00	2.31
Al(vi)	1.96	0.28		1.97	0.23	1.99	0.49	0.67	0.01
Ti	0.00	0.01						0.00	0.51
Fe'''	0.07	0.07		0.06	0.05	0.00	0.03	0.00	0.11
Cr	0.00	0.00						0.00	0.00
Fe''	1.34	0.10		1.41	0.14	1.24	0.09	0.60	1.66
Mn	0.04	0.00		0.03	0.00	0.02	0.00	0.01	0.00
Mg	0.96	0.56		1.01	0.58	0.62	0.41	0.28	3.39
Ca	0.64	0.67		0.53	0.73	1.11	0.53	0.11	0.00
Na	0.00	0.31		0.00	0.27	0.00	0.44	0.00	0.00
K	0.00	0.00						0.00	1.88
X(Ca)	0.21			0.18		0.37		0.11	X(Al)
Mg No.	41.58	84.79		41.78	80.61	33.14	81.50	31.82	0.00
Fe''/Fe(T)	5.06	58.97		0.04	0.40	0.00	0.29	0.00	X(Ti)
Fe/Mg	1.40	0.18		1.39	0.24	2.02	0.23	2.14	0.09
Z	3.00	2.00		3.00	2.00	3.02	2.00	1.00	0.49
Y	2.02	1.02		2.03	1.00	1.99	1.03	0.67	
X	2.98	0.98		2.97	1.00	2.99	0.97	1.00	
Pyp/Jad	**32.12**	**27.77**		**33.91**	**22.96**	**20.59**	**43.87**	**28.00**	
Alm/Aeg	**45.13**	**3.53**		**47.27**	**3.64**	**41.55**	**0.00**	**60.00**	
Spes/Tsc	**1.39**	**4.60**		**0.94**	**1.84**	**0.74**	**8.14**	**1.00**	
Gross	**18.01**			**15.12**		**37.13**		**11.00**	
And/Hed	**3.36**	**10.26**		**2.76**	**13.85**	**0.00**	**9.39**	**0.00**	
Uv/Diop	**0.00**	**53.84**			**57.71**		**38.60**	**0.00**	
K(D)	7.83			5.80		8.89		0.23	
ln K(D)	2.06			1.76		2.18		-1.48	
P(Kb)	T(C)								
	Krogh (1988)							I & M (1985)	
10	687			736		777		735	
12	692			742		782		743	
14	698			748		787		751	
16	703			754		793		760	
18	709			760		798		768	